

Electron Precipitation Associated with Discrete Very-Low-Frequency Emissions

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It has been known for some time that discrete VLF emissions from the magnetosphere are commonly observed just outside the plasmopause [Carpenter, 1963]. They may originate spontaneously or they may be triggered by whistlers and man-made VLF signals within the plasmopause near the plasmopause. It has been hypothesized that discrete VLF emissions are generated near the geomagnetic equator by a feedback mechanism involving cyclotron resonance between the waves and electrons [Brice, 1963, 1964a; Helliwell, 1967]. It is widely recognized that whistler-mode waves probably play an important role in the precipitation of electrons [Brice, 1964a, b; Kennel and Petschek, 1966]. However, no direct link between discrete VLF emissions and particle precipitation has previously been found.

Examples of indirect evidence linking discrete VLF emissions to electron precipitation are (1) the association between chorus and electron microbursts reported by *Oliven and Gurnett* [1968], (2) a positive correlation between chorus and riometer absorption [Helliwell, 1965; Ecklund et al., 1965], and (3) the sudden reduction in strength of VLF signals observed on satellites crossing the plasmopause toward high latitude [Heyborne et al., 1969].

In this letter we report preliminary results of a wave-particle experiment conducted near the plasmopause at Siple station, Antarctica ($L = 4.1$). Bremsstrahlung X rays, arising from the precipitation of energetic electrons, were recorded with sodium iodide scintillation counters (omnidirectional geometric factor 15 cm^2) flown on high-altitude balloons launched from Siple station. Several balloons also carried VLF

receivers provided by the Norwegian Institute of Cosmic Physics. During the periods when the balloons were aloft, continuous ground-based broad-band (0.2–28 kHz) VLF recordings were made at Siple station and its conjugate at Roberval, Quebec. Synoptic VLF recordings were made at Byrd station and its conjugate at Great Whale River.

During a period of enhanced activity at Siple station a one-to-one correlation was found between short bursts of X rays ($E > 30 \text{ kev}$) and bursts of VLF emissions with center frequency near 2.5 kHz. These observations are interpreted in terms of the cyclotron resonance interaction at the equator, and suggestions are made for further experiments. Further details of this and other events will be reported later.

OBSERVATIONS

The data of interest were obtained on January 2, 1971, during a gradual-commencement magnetic storm. Flight 6, launched at 0640 UT, reached ceiling altitude of $\sim 7 \text{ g/cm}^2$ at 0833 UT, approximately 4 hours after the start of the storm. An intense VLF event began at $\sim 0820 \text{ UT}$ (0320 LT), shortly before the balloon reached ceiling altitude. The first 15 min of the event consisted of unstructured noise in a band between 0.5 and 2 kHz. Some discrete emissions could be discerned by $\sim 0840 \text{ UT}$, becoming more evident with time. During this period no enhancement of the X-ray count rate above the cosmic-ray background level was noted. At $\sim 0845 \text{ UT}$ the character of the VLF emissions changed markedly; intense discrete rising tones appeared several seconds apart in the frequency band from ~ 1.5 to $\sim 4 \text{ kHz}$. Each emission occurred essentially in time coincidence with a short-duration burst of X rays. Several hundred examples of this correlation were noted over a 1-hour period.

The X-ray bursts were recorded in energy channels set for $E > 30$ and $E > 68 \text{ kev}$. The excess count rates in these two channels can be described by an exponential primary elec-

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tron-energy spectrum with e -folding energy $E_0 \approx 30$ keV. This suggests that the average energy of the electrons contributing to the bursts in the $E > 30$ keV X-ray channel was ~ 60 keV, with the range of electron energies extending from 30 to at least 100 keV. Later analysis of additional energy channels will permit a more precise estimate of the electron energies involved.

Emissions in the above frequency range were not observed at Byrd station, Antarctica, and were extremely weak on the records from Great Whale River, Canada. Since the intensity of the VLF emissions was relatively high at Siple station, the exit point from the ionosphere must have been very close to that station. For later analysis, these emissions are assumed to exit the ionosphere at $L = 4.2$ (the balloon location). Below 1 kHz a band of VLF emissions was seen with roughly equal intensity at Siple station and at Byrd station, thus placing the ionospheric exit point of this band approximately midway between the two stations. At Roberval discrete VLF emissions were seen in the same frequency band as at Siple station, but there were no identifiable correlations between the individual elements. Furthermore, the VLF bursts associated with X rays at Siple station were stronger and more complex than those at Roberval and were suggestive in spectral character of emissions triggered by whistlers. Study of whistler traces observed at Siple station at ~ 1038 UT and the observation at Roberval of a few spherics that correlate with the noise bursts associated with X rays suggest that all these bursts were triggered by whistlers from lightning discharges in the northern hemisphere (D. L. Carpenter, private communication, 1971).

To date, 2 min of data have been analyzed in detail. Samples of these data are illustrated in Figures 1 and 2. Figure 1 shows a 30-sec segment of the counting rate of the $E > 30$ keV X-ray channel, a 0- to 5-kHz f - t spectrogram, and the VLF amplitude integrated between 0.6 and 5 kHz. Similar data are presented in Figure 2 for one intense X-ray/riser pair. Salient features of these records, supported by less detailed examination of the bulk of the data, are summarized below.

1. Every major burst of X rays is associated

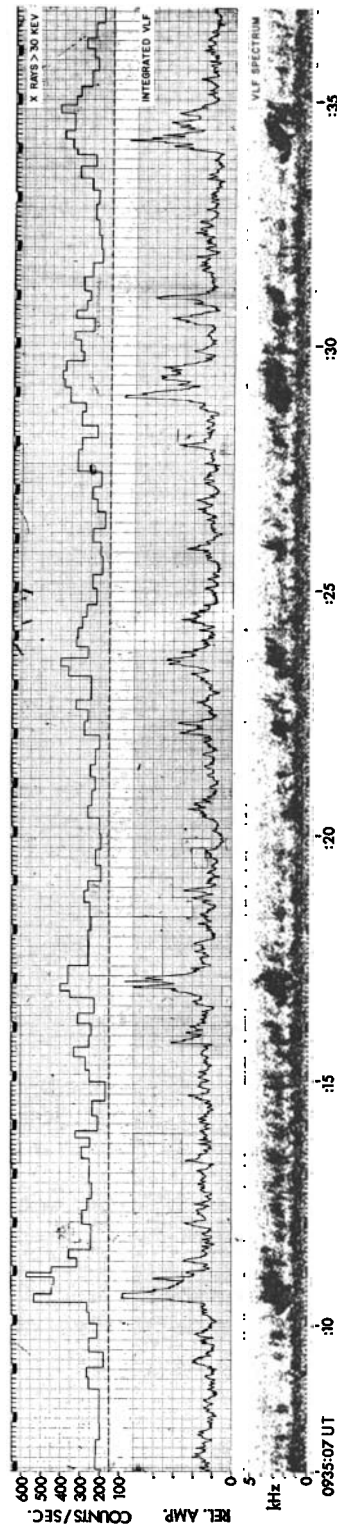


Fig. 1. A 30-sec segment of simultaneous recordings of X-ray count rate for $E > 30$ keV (top), integrated VLF amplitude from 0.6 to 5 kHz (middle), and VLF spectrum from 0 to 5 kHz (bottom), at Siple station, Antarctica, on January 2, 1971. The dashed line in the top portion of the figure refers to the cosmic-ray background level of ~ 175 c/sec. (Because of a plotting error the X-ray record must be shifted 0.15 sec to the right relative to the VLF records; no correction is required in Figure 2.)

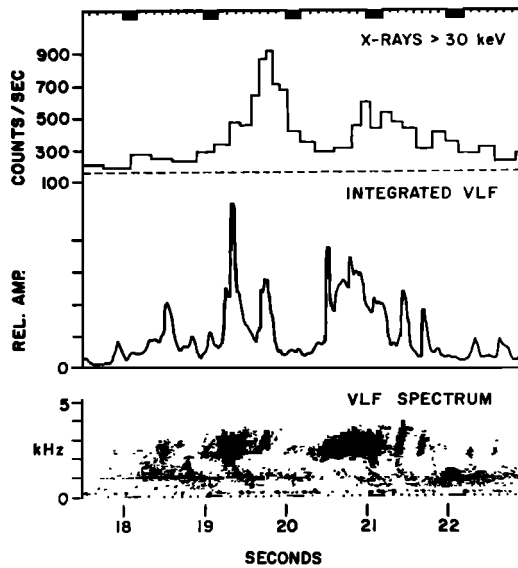


Fig. 2. Unusually intense X-ray burst and corresponding VLF data (integrated VLF redrawn) from same data set from which Figure 1 was taken. Data are from Siple station, on January 2, 1971, at 0936 UT.

with the emission of VLF rising tones of essentially the same duration (~ 0.5 -3 sec). The converse relation was also found to be true.

2. Where time resolution in the X-ray data permits, some corresponding substructure can be noted in a given X-ray/riser pair. Note also that, in the intervals between X-ray bursts, the counting rate returns approximately to the background level.

3. Larger X-ray bursts tend to be associated with stronger emissions.

4. Emissions correlated with X-ray bursts are bandlimited between ~ 1.5 and 4 kHz with center frequency near 2.5 kHz.

5. Correlated X-ray/riser pairs occur quasi-periodically with dominant period near 6 sec.

6. VLF emissions precede X-ray bursts by several tenths of a second.

As indicated below, points 5 and 6 are confirmed only for the limited sample of data that has thus far been analyzed in detail.

STATISTICAL ANALYSIS OF X-RAY AND VLF RECORDINGS

The 2 min of X-ray and VLF data from 0935 to 0937 UT have been subjected to power-

and cross-spectrum analysis. The methods used and estimation of errors are described by Bendat and Piersol [1966].

Since the noise band below 1 kHz was unrelated to the occurrence of the X-ray bursts, only the integrated VLF amplitude between 1.44 and 3.84 kHz was used. These data and the $E > 30$ keV counting rate were digitized at 0.1-sec intervals. Statistical fluctuations were then smoothed by applying to the digitized values a 5-point equal-weight moving average. Power spectra, normalized cross-covariance, and coherence of the smoothed data were computed by using a maximum of 120 lags. The results are presented in Figures 3 and 4.

To summarize the most important points, we note the following. (1) The power spectra of the X-ray and VLF recordings are similar, with peak power centered at the 6-sec period. (2) The data are strongly coherent at the 6-sec periodicity ($\gamma^2 = 0.88$). (3) The peak in the cross-covariance is shifted ~ 0.3 -0.4 sec in the direc-

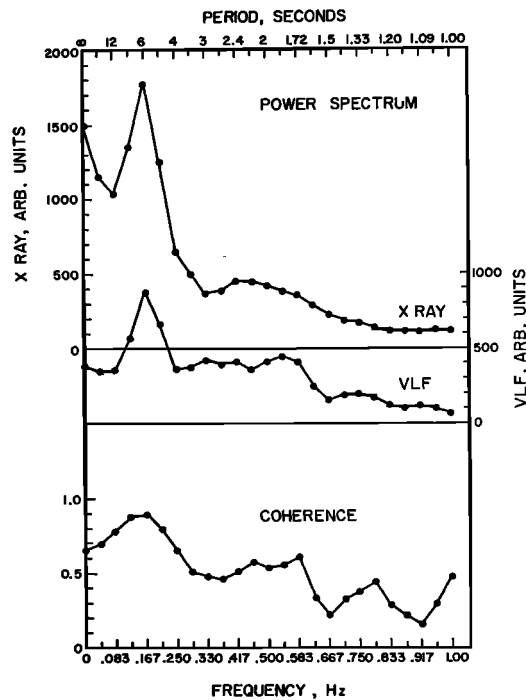


Fig. 3. Power spectra of X-ray (upper) and VLF (middle) intensities and coherence (lower) of X-ray and VLF intensities. The only significant spectral peak occurs at a 6-sec period.

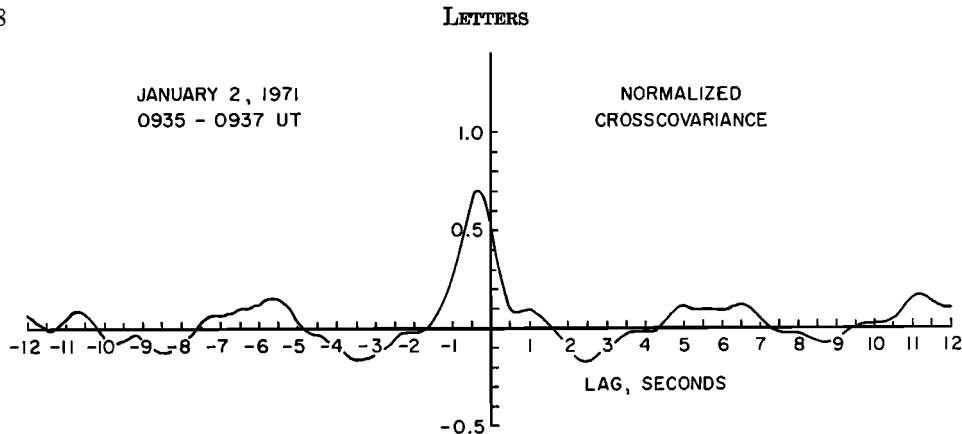


Fig. 4. Normalized cross-covariance of X-ray and VLF intensities as a function of the time lag of the VLF intensity with respect to the X-ray count rate. Maximum correlation corresponds to VLF emissions leading X-ray bursts by $\sim 0.3-0.4$ sec.

tion that favors the earlier arrival of VLF emissions.

INTERPRETATION

Helliwell [1967] has advanced a phenomenological theory, based on cyclotron resonance, to account for the generation of variable-frequency discrete VLF emissions. Within the interaction region, energetic electrons are phase-correlated by circularly polarized waves in the whistler mode and then radiate. This loss in energy of the interacting electrons results in lowering of their mirror altitudes, as shown by *Brice* [1964a, b]. Because the resonance condition requires that the Doppler-shifted wave frequency be matched to the electron gyrofrequency, the cyclotron radiation and the resonant electrons travel in opposite directions along the field line. The frequency-time profile of emitted radiation depends on the position of the interaction region with respect to the equator. In particular, rising tones are produced when the interaction region is on the downstream side (i.e., electrons moving in the direction of increasing gyrofrequency), whereas falling tones are generated when the interaction region is on the upstream side. Constant frequency tones are generated on the equator. Actual displacement of the interaction region from the equator is usually quite small (~ 1000 km) and has been neglected in the calculation of travel times.

A schematic illustration of the theory as it applies to the present results is shown in Figure 5. Several points in connection with this

figure require elaboration. For the emission to be detected at Siple station it must be directed so initially, since it is not observed at Roberval (other, less intense, discrete emissions are seen at Roberval but appear to be independent of those at Siple station). The fact that the observed emissions were mainly rising tones indicates that the interaction region must be located on the northern-hemisphere side of the equator, as indicated, with the resonant electrons heading (initially) toward the northern conjugate point. To account for bremsstrahlung X-ray bursts occurring at Siple station, some fraction of the resonant electrons would have to mirror in the north and then be lost over Siple station. Asymmetry in the conjugate mirror point altitudes for the Siple station-Roberval field line favors this explanation; a mirror height of 100 km at Siple station corresponds to a conjugate mirror height of 280 km over Roberval [*Barish and Wiley, 1970*]. This point is probably not too critical to the argument, however, since the resonant electrons can be expected to have a broad range of pitch angles, and a fraction of precipitated electrons ($\sim 10\%$ on the average) are backscattered. A later report will compare a theoretical estimate of the flux of resonant electrons with that deduced from the bremsstrahlung measurements.

A more critical test of the theory involves a comparison of the predicted electron energy and the relative arrival times of electrons and waves with the measured energy and time delay (VLF leading X rays by $\sim 0.3-0.4$ sec). To obtain

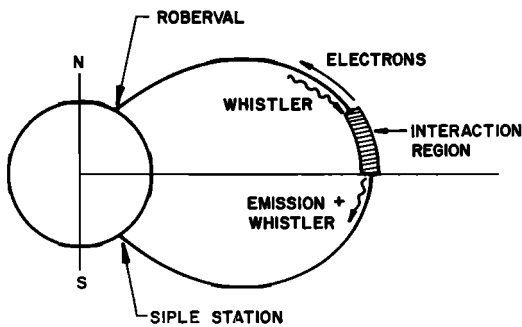


Fig. 5. Schematic drawing of the mechanism postulated to explain association between X-ray bursts and discrete VLF emissions.

relevant numbers, we assume that the interaction region is on the equator at $L = 4.2$, the estimated L value of the E region above the balloon. We further assume average conditions of steady, moderate agitation in the magnetosphere; the path of propagation is then outside the plasmapause and the equatorial electron density is 10 el/cc [Angerami and Carpenter, 1966].

The relative time of arrival was computed by subtracting the 3/2 travel time of the resonant electrons from the 1/2-hop travel time of the emission, starting at the equator. The 1/2-hop whistler-mode group delay is given by

$$t_w = \frac{1}{c} \int_0^{\lambda_m} \mu_G \frac{ds}{d\lambda} d\lambda$$

where c is the velocity of light; s is the distance along the field line; λ is the geomagnetic latitude; λ_m is the latitude of exit point of emission from ionosphere ($\approx 61^\circ$), also the electron mirror point latitude in bounce-time calculation below; and μ_G is the full expression for the group refractive index given by Angerami [1966].

The 3/2 bounce time of the resonant electrons is given by

$$t_e = (3LR_0/v)F(\lambda_m)$$

where L is McIlwain's parameter, R_0 is the mean earth radius, v is the total velocity of resonant electron, and $F(\lambda_m)$ is an integral function of mirror point latitude tabulated by Hamlin *et al.* [1961; see also Rossi and Olbert, 1970].

Since the equatorial pitch angle of the loss

cone on the $L = 4.2$ field line is $\sim 5^\circ$, we assume $v \approx v_{||}$, the component of resonant electron velocity along the magnetic-field line at the equator. Then $v_{||}$ is obtained from the resonance relation

$$f_{H'} = f + (k/2\pi)v_{||}$$

with the wave number

$$k = \frac{2\pi f}{c} \left[1 + \frac{f_N^2}{f(f_H - f)} \right]^{1/2}$$

and where f is the wave frequency, f_N is the electron plasma frequency, f_H is the gyrofrequency of thermal electrons, and $f_{H'}$ is the gyrofrequency of resonant electrons corrected for relativistic mass change.

The values of electron energy (and corresponding parallel velocity at the equator) and relative time of arrival are shown in Figure 6 for frequencies of 2, 3, and 4 kHz. This range of frequencies includes most of the VLF burst energy. A diffusive equilibrium as well as an R^{-4} density model was used. In addition to the

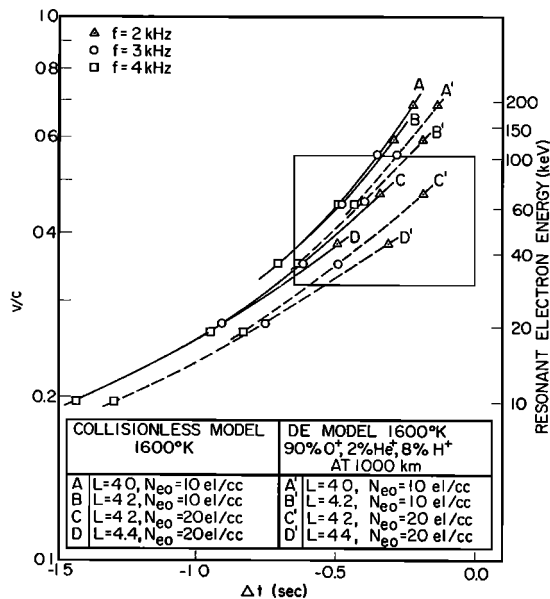


Fig. 6. Relation of resonant electron energy (right-hand ordinate) and corresponding normalized parallel velocity (left-hand ordinate) to the relative time of arrival of the wave packet and the X-ray bursts, for different models of the magnetosphere and different wave frequencies. The rectangle represents the estimated range of the measured electron energy and the relative time.

nominal model, with $L = 4.2$ and 10 el/cc, other curves are shown for $L = 4.2$, 20 el/cc; $L = 4.0$, 10 el/cc; and $L = 4.4$, 20 el/cc. The rectangular area, centered on the measured values of time delay and average energy of precipitated electrons, represents the estimated range of observed values of electron energy and relative times. It is seen that the agreement is excellent for $L = 4.2$, (the balloon location) and for electron density between 10 and 20 el/cc. Using whistler data from the Siple station tapes, D. L. Carpenter (private communication, 1971) estimates the actual plasmapause position to be $L = 3.8_{-0.1}^{+0.4}$ and the equatorial electron density on the $L = 4.2$ field line to be 25 ± 12 el/cc. These results support our deductions based on the energy and relative time measurements. They suggest that this type of experiment might be used to measure the equatorial electron density.

DISCUSSION

In the previous section we showed that the measured time difference in the X-ray/riser correlation could be adequately explained by Helliwell's theory of the generation of discrete VLF emissions [Helliwell, 1967]. Thus we take these results to be a confirmation of that theory and suggest that these data represent the first direct experimental evidence for an electron precipitation effect related to cyclotron resonance on magnetospheric-field lines.

On two previous occasions [Oliven and Gurnett, 1968; Gendrin *et al.*, 1970] a search was made for detailed correlations in the fine structure of VLF radio noise and trapped and precipitated energetic electrons. Apart from a general association of electron microbursts with the occurrence of chorus [Oliven and Gurnett, 1968], these investigations failed to disclose a detailed correspondence between individual chorus elements and changes in the electron flux. In the Injun 3 study of Oliven and Gurnett, some electron microbursts and chorus elements seem to be paired (see their Figure 6). However, they note that a one-to-one association between microbursts and individual chorus elements was not generally observed. They suggest that this lack of a detailed correlation is related to the fact that the satellite observes waves that tend to deviate from the field line (i.e., nonducted emissions), whereas the electrons

are constrained to follow the field lines. Limited instrumental time resolution and the short observational time in the rocket experiment of Gendrin *et al.* may have contributed to the lack of correlation in that experiment. However, since the occurrence of chorus is not always accompanied by microbursts [Oliven and Gurnett, 1968], their negative result is not unexpected.

In any case, it is not clear that the microburst/chorus association is related to the present observations. Although the X-ray data lack sufficient resolution to rule out the presence of microbursts, the measurements were made at ~ 0330 LT and $\sim 61^\circ$ invariant latitude, a combination of time and latitude that rarely shows the presence of microbursts [Oliven *et al.*, 1968]. Furthermore, the discrete emissions reported here for the most part bear little resemblance to the closely spaced elements of a few tenths of a second duration that are typical of chorus.

Since in a number of instances it has been established that the discrete emissions recorded at Siple station were triggered by whistlers, it is clear that the electron precipitation bursts were caused by the discrete emissions, rather than the reverse. Appreciable triggering by whistlers would lead to the hemisphere asymmetry in emission generation suggested by the data; namely, since almost all whistlers on the Siple station-Roberval field line originate from lightning discharges in the northern hemisphere, both the triggering waves and the emitted radiation would propagate in the direction indicated in Figure 5. This result is in agreement with previous studies showing that periodic emissions are started by waves rather than particle bunches [Helliwell, 1965].

One feature of the data not specifically treated by the theory discussed is the quasi-periodic (period ~ 6 sec) occurrence of the emissions. Multiple triggering related to whistler-mode echoing cannot account for this periodicity because the period is too long and is not regular enough. Emission trains attributed to whistler-mode echoing show precise periods [Helliwell, 1965]. Discounting the appearance of such a periodicity in lightning discharges, the explanation must be sought elsewhere. One possibility is that magnetic micropulsations exercise some control over the emission process (although triggering by whistlers would still be required),

perhaps in a manner similar to that suggested by *Coroniti and Kennel* [1970]. The dominant periodicity would then be governed by the micropulsation spectrum. Data from the Bell Laboratories magnetometer at Siple station revealed weak micropulsations with a 6-sec period (L. Lanzerotti, private communication, 1971).

POSSIBILITY OF CONTROLLING ELECTRON PRECIPITATION

Discrete emissions can be stimulated artificially by using ground-based transmitters operating in the VLF range [*Kimura*, 1968; *Helliwell et al.*, 1964]. Since the observations reported here indicate that the generation of discrete emissions causes the precipitation of energetic electrons, one may expect that controlled stimulation of VLF emissions will lead to the controlled precipitation of energetic electrons into the ionosphere.

Experiments in the next several years from Siple station and Roberval will examine this and other relationships. In January 1972, Siple station will become a year-around scientific facility with the capability of supporting several experiments to monitor the plasmopause and to pursue further studies of wave-particle interactions and their resultant effects. A 150-kw VLF transmitter will be used to stimulate VLF emissions. Balloon-borne X-ray detectors will again be launched to measure energetic particles precipitated in the interaction process.

At a time when increased emphasis is being placed on ground-based methods to study the magnetosphere, the present results offer exciting possibilities for future studies of the physics of magnetospheric wave-particle interactions at moderate cost and under conditions similar to the laboratory.

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