A Subauroral and Mid-Latitude View of Substorm Activity

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A substorm period near 0900 UT on January 2, 1971, provided both new and confirming evidence of mid-latitude and subauroral phenomena associated with magnetospheric substorm activity. Several of the principal ground and/or balloon observations were made near $L = 4$ at the conjugate stations Siple, Antarctica, and Roberval, Canada. Satellite data were obtained from ATS 5, positioned at synchronous orbit roughly 2 hours to the west of the Siple-Roberval meridian. A key feature of the substorm activity was the previously reported observation of correlated bursts of X rays and VLF noise. It has earlier been concluded that the VLF bursts and associated particle precipitation events were 'triggered' by whistlers entering the magnetosphere at $L \sim 4$ outside but near the plasmapause. During the substorm period a widespread VLF phase anomaly (previously reported) was observed on subionospheric paths extending within the plasmasphere to $L \sim 2.5$ and over much of North America. Conjugate ULF observations near $L = 4$ revealed enhancements of noise power in the 8- to 128-s period range at times of individual substorm intensifications and also a large increase in noise power during the period of correlated X ray and VLF burst activity. Conjugate VLF observations revealed a series of noise bands at frequencies below 3 kHz, with durations of the order of 30 min and center frequencies generally rising with time. The onset of each band appeared to follow within less than 10 min a substorm intensification detected from ground magnetometers or ATS 5 energetic particle detectors. Cross-L inward drifts of whistler paths were observed in the outer plasmasphere during the substorm activity. The inferred westward electric field averaged about 0.35 mV/m during the hour before the observations of correlated X ray and VLF bursts. During this hour the plasmapause appears to have been displaced to a position slightly equatorward of Siple; in terms of resonance conditions along the field lines, the X ray detectors on the balloon over Siple were then in a favorable position to observe the results of magnetospheric wave-particle interactions involving electrons of energy greater than 30 keV. The various observed phenomena show promise of providing information on (1) the relations of ULF and VLF noise activity to the magnetospheric particle population at middle latitudes, (2) the injection and subsequent drift of low and medium energy electrons during substorms, and (3) enhanced particle precipitation deep within the plasmasphere during substorms.

INTRODUCTION

A conjugate experiment conducted at $L \sim 4$ on January 2, 1971, provided evidence that a whistler wave entering the magnetosphere in one hemisphere may give rise to electron precipitation in the conjugate region [*Rosenberg et al.*, 1971]. The precipitation event, detected by balloon-borne X ray and ground-based VLF techniques using the Siple (Antarctica) and Roberval (Canada) conjugate pair, occurred outside the plasmasphere within a several-hour period of repeated substorm intensifications. During this period a variety of other wave and particle phenomena, apparently related to the substorm activity, was observed within the plasmasphere, near the plasmapause (at $L \sim 4$), and at synchronous orbit. For example, a VLF phase anomaly occurred well within the plasmasphere [*Potemra and Rosenberg*, 1973], and enhanced activity in the convection electric field and in ULF and VLF noise was observed near the plasmapause. The following brief descriptive report, which brings together both material previously published and some additional observational results, is intended to motivate further research into subauroral and mid-latitude substorm effects.

A full chronological description of the substorm activity on January 2, 1971, will not be attempted here; rather, various apparently interrelated features of the event will be touched upon briefly. In separate papers, *Foster and Rosenberg* [1975] and *Foster et al.* [1975] discuss and interpret the detailed features of the correlated VLF and X ray bursts at $L \sim 4$ and examine the relationship of the various observations to the occurrence of substorm intensifications and particle injection events.

EXPERIMENTAL OBSERVATIONS

Figures 1 and 2 illustrate some of the interrelated observations that will be described below. Figure 1 shows in meridian cross section of the magnetosphere a diagram of observations made in the vicinity of the Siple-Roberval meridian (~75°W) during the January 2, 1971, event. This figure points out the location of sensors and describes the observed geophysical phenomena. The time dependence of some of these phenomena is shown in Figure 2 for the period 0700–1200 UT. The approximate relations between universal time and magnetic local time at the Siple-Roberval meridian and at ATS 5 are shown above the upper time scale. Marked with arrows near the upper and lower time scales of Figure 2 are the

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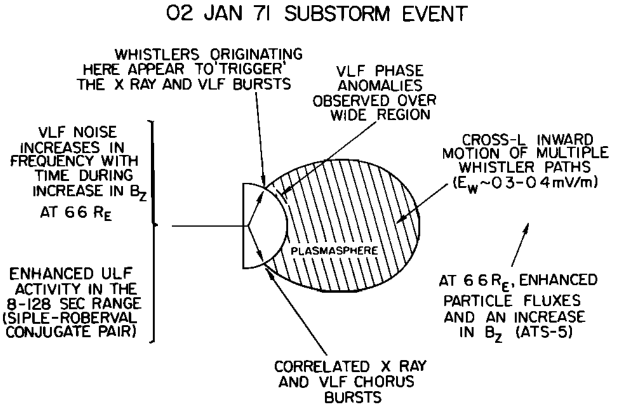

Fig. 1. Meridian cross section of the magnetosphere showing observations made in the vicinity of the Siple-Roberval meridian during the substorm event of January 2, 1971.

approximate times of substorm intensifications (0730, 0820, 0850, and 0925 UT) identified by *Foster et al.* [1975].

Figure 2*a* presents the B_z magnetic component measured on ATS 5 ($L \sim 6.6$) by the Goddard Space Flight Center magnetometer (W. C. Skillman, personal communication, 1972). ATS 5 was positioned ~2 hours to the west of the Siple-Roberval meridian. Figure 2*b* contains the 40-keV electron counting rates recorded on ATS 5 by the University of California at Berkeley instrument (F. S. Mozer, personal communication, 1972). Magnetic field variations and particle enhancements are noted in conjunction with some of the substorm intensifications. These data and their relationship to the accompanying substorm activity are discussed elsewhere [*Foster et al.*, 1975].

Contained in Figure 2*c* are the count rates for X rays with energy $E > 30$ keV recorded by a University of Maryland balloon experiment over Siple [*Rosenberg et al.*, 1971]. Figure 2*d* shows the time dependence of the phase of a VLF signal transmitted at 17.8 kHz from Cutler, Maine (NAA), to the Applied Physics Laboratory (APL), Maryland [*Potemra and Rosenberg*, 1973]. Figure 2*e* presents 5-min averages of ULF noise power in the period range 8–128 s recorded by Bell Laboratories magnetometers at Girardville, Quebec ($L = 4.4$), and at Siple Station. The Quebec site is slightly poleward of the calculated northern hemisphere conjugate of Siple [*Lanzerotti et al.*, 1975]. Figure 2*f* shows the westward component of the magnetospheric equatorial electric field in the outer plasmasphere as inferred from whistlers recorded by the Stanford group at the Siple-Roberval conjugate pair.

We now briefly describe some of the observations presented in Figures 1 and 2.

Correlated X ray and VLF chorus bursts. Figure 3, from *Rosenberg et al.* [1971], compares the response of a balloon-borne X ray detector flown over Siple Station, Antarctica, to continuous broad band VLF recordings made on the ground at Siple. The upper panel of Figure 3 shows the count rate for X rays of $E > 30$ keV. In the middle panel is plotted the broad band VLF amplitude over the frequency range of ~0.6–5 kHz. The bottom panel contains the VLF dynamic spectrum, the darkness of the display crudely indicating the intensity of the VLF signal. The interval shown is approximately 30 s in duration from 09h 35m 07s to ~09h 35m 35s (cf. Figure 2). There is evidently a close correlation between the X ray and the VLF bursts occurring at intervals of ~6 s in this part of the event [*Rosenberg et al.*, 1971].

Using information that included measured small differences in arrival time between the VLF bursts and the X ray bursts and measurements from whistlers of magnetospheric plasma density, *Rosenberg et al.* [1971] concluded that the VLF bursts had been generated in the equatorial region of the magnetosphere through a cyclotron resonance interaction with whistlers and that pitch angle scattering from the enhanced wave activity had given rise to the observed precipitation events.

Enhancement of the X ray flux above background began at ~0840 UT, but the period of correlated bursts was limited to the interval of ~0920–0945 UT, indicated by the solid bar in Figure 2*c*. Other relationships between the X ray activity and the relatively complex patterns of VLF noise have been discussed by *Foster* [1973].

In the study of the correlated X ray and VLF bursts it was found that the VLF bursts were triggered by whistlers. Triggering by whistlers was inferred from an analysis of simultaneous broad band VLF recordings at Siple and Roberval. The data showed that the shape in frequency versus time of the correlated VLF bursts was similar to that of bursts clearly triggered by whistlers later in the substorm event [*Foster*, 1973; *Foster and Rosenberg*, 1975]. Also, the bursts resembled closely a type of VLF noise that is known from many other observations to be triggered by whistlers. The whistler analysis, coupled with supporting broad band information from the Stanford University VLF experiment on the Ogo 6 satellite, which passed near Roberval at the time of the observations, further revealed that the correlated X rays and VLF bursts were occurring on field lines near to but outside the plasmapause (the estimated location of the plasmapause at 0930 UT was $L = 3.8 \pm ^{0.1}_{0.1}$). It was also determined that equatorial electron concentrations beyond the plasmapause were not at the low levels characteristic of strong, persistent disturbance but instead were at intermediate levels (of the order of 10 cm^{-3}), more characteristic of recovery periods for this LT interval [see *Corcuff et al.*, 1972].

VLF perturbations within the plasmasphere. The effects of

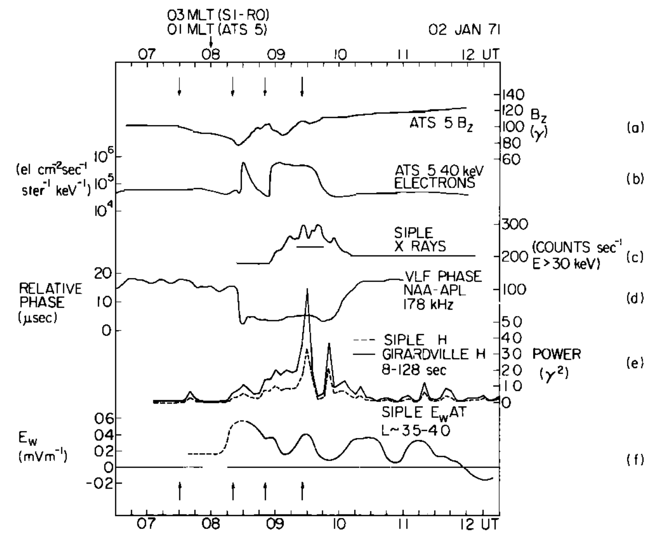

Fig. 2. The correlated time dependence of the substorm-associated phenomena indicated in Figure 1. Arrows near the upper and lower time scales indicate the approximate times of substorm intensifications identified by *Foster et al.* [1975]. Curve *c*, showing Siple X rays, was adapted from a figure from *Potemra and Rosenberg* [1973]. See text for further details.

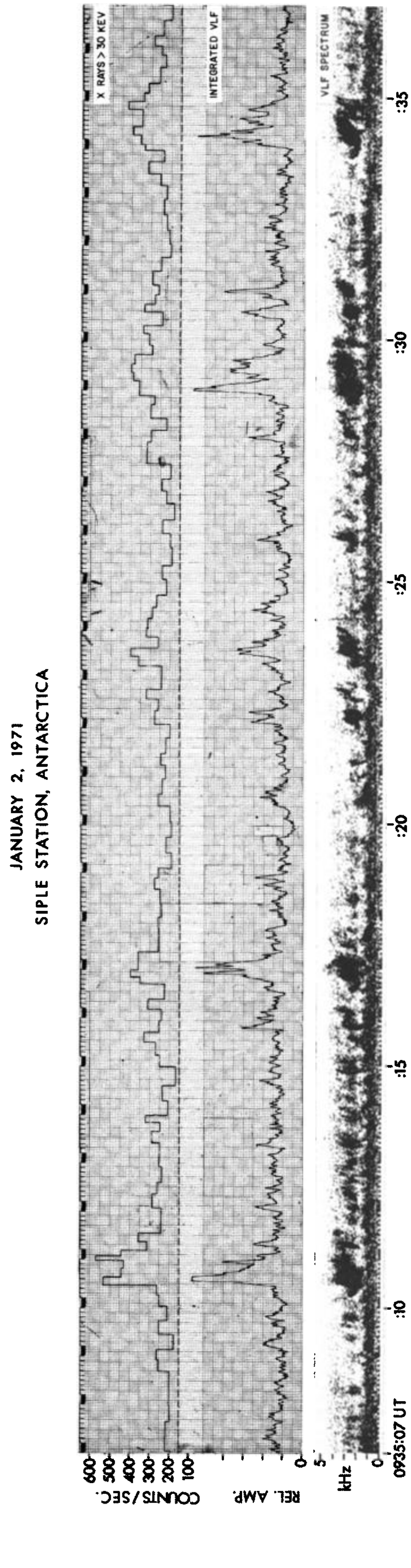

Fig. 3. Simultaneous balloon X ray and ground VLF measurements at Siple, Antarctica ($L \sim 4$), showing one-to-one correlations between bursts of X rays and of VLF noise [from *Rosenberg et al.*, 1971]. The upper panel shows the count rate for X rays of $E > 30$ keV. The middle panel shows broad band VLF amplitude over the frequency range of ~0.6–5 kHz. The bottom panel shows the VLF dynamic spectrum from 0 to 5 kHz.

the January 2, 1971, substorm activity were detected deep within the plasmasphere in the form of well-documented anomalies in the phase of man-made VLF signals propagating between various stations in the night side northern hemisphere. This effect is illustrated by the phase record in Figure 2*d*. A phase advance of ~10 μs developed rapidly near the substorm intensification at ~0820 UT and lasted until after the intensifications identified at 0850 and 0925 UT. This VLF phase anomaly and its evident connection to substorm activity were reported by *Potemra and Rosenberg* [1973]. These authors discussed the possibility that precipitating energetic electrons ($E > 40$ keV) could produce the observed effects through enhancement of ionization below the normally undisturbed nighttime VLF reflection level of about 85 km. In their discussion, Potemra and Rosenberg showed that nighttime VLF phase is very sensitive to small numbers of precipitating electrons ($\lesssim 10^8$ cm^{-2} s^{-1} sr^{-1}) that would be only marginally detectable, if at all, by other indicators of electron precipitation such as bremsstrahlung X rays and riometer absorption.

Rosenberg and Saus [1974] have found further evidence of the scope and variety of mid-latitude precipitation effects through use of phase information from many trans-North America propagation paths. Figures 4 and 5 show the application of this method to the January 2, 1971, event, using a more extensive set of data than that previously presented. Figure 4 shows the distribution of VLF transmitter and receiver sites and the relation of associated great circle propagation paths to magnetic L shells at 100-km altitude. Figure 5 shows 16 phase path recordings for January 2, 1971, ordered in descending L value with respect to the highest L shell alqng each path.

Analysis of the phase changes from this grid of paths indicates that a phase advance associated with the substorm intensification at ~0820 UT occurred on a majority of the paths. On most of the perturbed paths the phase shift event lasted until 1000 or 1100 UT. Between ~0850 and 0910 UT, several paths exhibited secondary maxima that may have been associated with the substorm intensification at 0850 UT. Owing to the long lengths of most propagation paths and the fact that only a fraction of the total path length may be affected, it is difficult to describe precisely the extent of the perturbed region. None of the paths shown in Figure 4 exceed $L = 3.6$; as was mentioned earlier, whistler data show that the plasmapause was near to but slightly poleward of that magnetic shell during the period of interest. Of the paths that reached $L \geq 2.5$, only the paths NAA-NELC (44.7°N, 67.3°W–32.8°N, 117.1°W), NLK-NOBHA (48.2°N, 121.9°W–21.5°N, 158°W), and OM/T-DEAL (10.7°N, 61.6°W–40.3°N, 74°W) failed to respond significantly at 0820 UT. The magnitude of the phase change was small on paths below $L = 2.5$.

The data suggest that the perturbed mid-latitude region was confined in longitude within the essentially cross-L paths NLK-NOBHA and OM/T-DEAL located, respectively, at the western and eastern ends of the grid of Figure 4. In latitude, the phase effects reached equatorward to at least $L = 1.7$, major perturbations being limited to $L \geq 2.5$. Interference between wave modes in the earth-ionosphere wave guide may have contributed to the lack of response on the NAA-NELC path ($L = 3.6$), located within the perturbed region.

ULF observations. As is indicated in Figures 1 and 2, there was enhanced magnetic pulsation activity at Siple and in the conjugate region during the January 2, 1971, substorm activity. A flux gate magnetometer with digital data acquisition and storage [*Lanzerotti et al.*, 1972] was operated at Siple Sta-

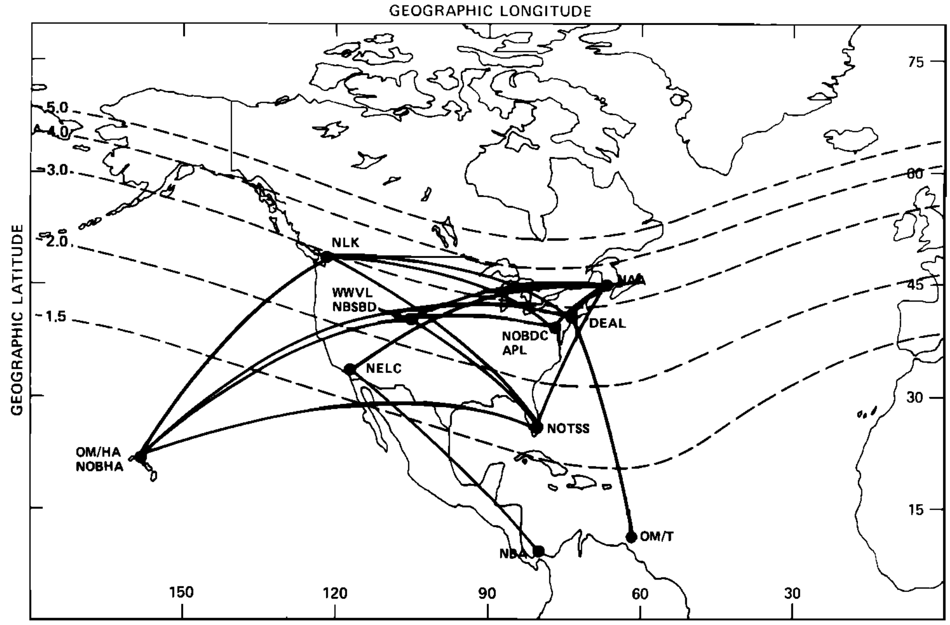

Fig. 4. Distribution of northern hemisphere VLF transmitter and receiver sites and the relation of associated great circle propagation paths to magnetic L shells at 100-km altitude.

tion. In addition, three similar magnetometer stations were operated in a latitudinal array in the area conjugate to Siple in Quebec, Canada. The data from these stations are used to study the degree of conjugacy of magnetosphere- and ionosphere-produced geomagnetic pulsations and disturbances near the plasmapause.

The ULF data showed variations apparently associated with the substorm activity. Plotted in Figure 6 are the dynamic power spectra of the geomagnetic disturbance levels (H component) observed in the 5- to 35-mHz frequency band (normal Pc 3-Pc 4 magnetic pulsation band) at Siple and at two of the northern hemisphere stations, Lac Rebours (L = 4) and

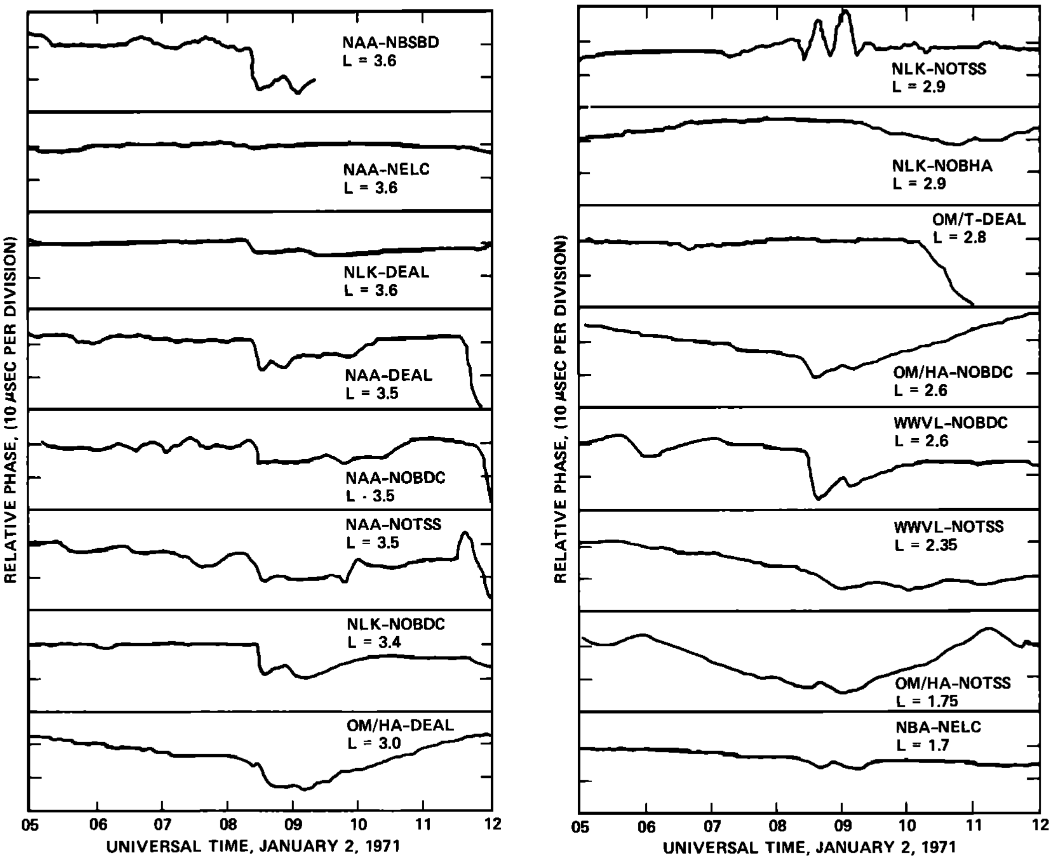

Fig. 5. VLF phase path recordings for the period 0500–1200 UT on January 2, 1971, ordered in descending L value with respect to the highest L shell along each path. See Figure 4 for identification of transmitter and receiver locations.

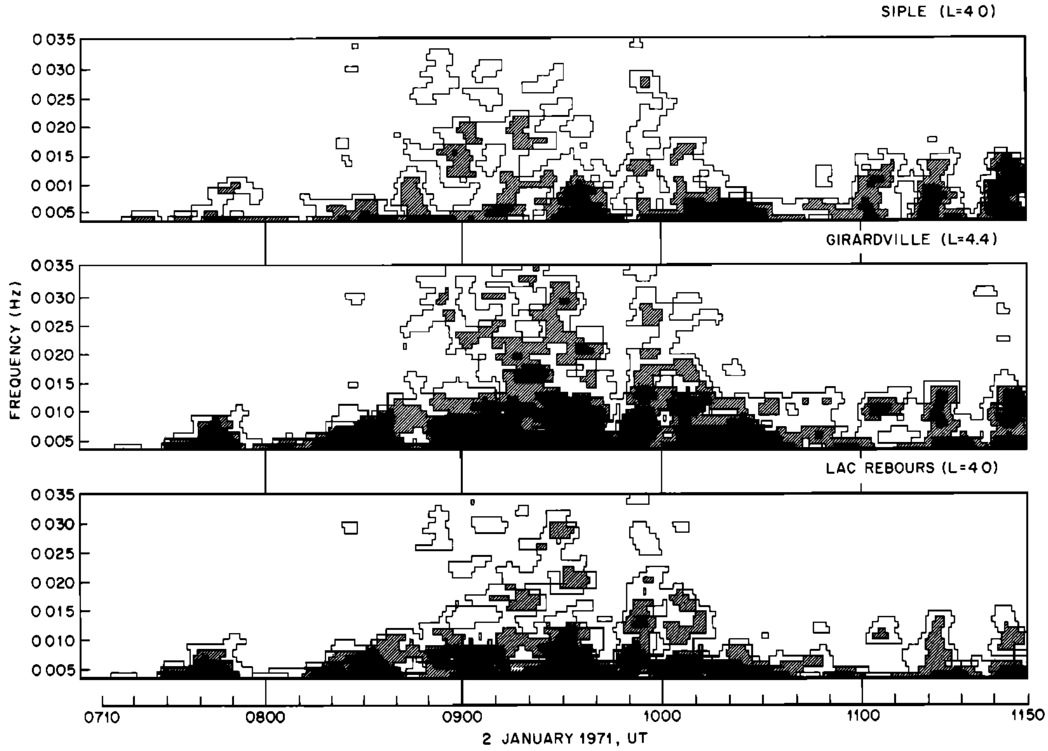

Fig. 6. Dynamic power spectra of the geomagnetic disturbance levels (H component) observed in the 5- to 35-mHz frequency band at Siple and at two of the northern hemisphere stations for the interval 0710–1150 UT on January 2, 1971.

Girardville (L = 4.4), for the interval 0710–1150 UT (0210–0650 MLT) on January 2, 1971. Each contour corresponds to 5 dB in power level (0 dB = 3 γ^2/Hz).

The data in Figure 2e (presented earlier) contained the integrated power levels for Girardville and Siple over the 5- to 35-mHz band shown in Figure 6. Thus both Figure 2 and Figure 6 show enhancements of ULF power levels near the times of substorm intensifications at 0730, 0820, 0850, and 0925 UT. After 0820 UT the noise activity became more broad band, and during much of the activity the power levels in the northern hemisphere exceeded those measured in the conjugate region (Figure 6).

A particularly large enhancement in power occurred in the interval of ~0920–0940 UT, at approximatley the time of the correlated VLF and X ray burst activity (bar in Figure 2c). The enhancement was generally more pronounced in the northern hemisphere, and it also exhibited a sharp latitudinal gradient in the north, with higher power levels at L = 4.4 than at L = 4.

VLF observations. Broad band VLF recordings at Siple and Roberval resemble the ULF data in that they show beginnings or intensity increases of noise near the times of substorm intensifications. Figure 7, top and middle panels, compares 0- to 5-kHz frequency-time records for Roberval and Siple in the period 0800–1020 UT. The bottom panel shows the Siple record in the 0- to 2.5-kHz range. Arrows along the time scale indicate the substorm intensifications at ~0820, 0850, and 0925 UT.

VLF noise activity was strongly enhanced at Siple near 0820 UT. Between ~0835 and 0900 UT a noise band with a center frequency that rose from ~2 to ~3 kHz was detected at both Siple and Roberval. Siple also shows intense activity in the range ~500–1500 Hz between ~0820 and ~0905 UT (the Roberval spectrum below ~700 Hz was filtered to reduce local power line interference). Quantitative comparisons of signal levels at the two conjugate stations have not been made, but if the rising noise band is assumed to be of comparable wide band intensity at the two stations, then much of the noise activity below ~2 kHz appears to occur preferentially at Siple.

Near 0900 UT, shortly following the intensification at 0850 UT (arrow), a noise band starting in the 200- to 400-Hz range and broadening to ~600 Hz in width appeared at Siple (see bottom panel). The center frequency of the band rose with time; the lower edge of the band shows a relatively smooth rise from ~200 Hz at ~0900 UT to ~500 Hz at 0925 UT. Another band appeared between 0930 and 0935 UT, shortly after the intensification at ~0925 UT. The noise was centered near ~800 Hz and exhibited a series of several-minute-long bursts about 1 kHz wide. Again the lower edge of the band appears to rise, in this case from ~300 Hz at 0935 UT to ~500 Hz at 0955 UT.

The VLF noises that were correlated with the X ray bursts in the 0920–0945 period appear on the Siple records as irregular essentially vertical lines in the frequency range of ~2–4 kHz (see middle panel). They begin at ~0915 UT, near the beginning of the burst correlation period, and extend well past its end at ~0945 UT. In this period there were similar noise bursts at Roberval, but they appeared to be substantially less intense and fewer in number than those detected at Siple.

With the possible exception of the period of ~0820–0830 UT, all of the noise activity at Siple appears (on an expanded time scale) to be irregular and burstlike. Many bursts appear to have been triggered by whistlers, and many noise elements in two bands separated in frequency (near 0845 UT, for example) are connected by rising tones of relatively low intensity. This suggests that noise elements of both bands propagated on the same magnetospheric path.

Westward electric field in the outer plasmasphere. At ~0825 UT, near the time of a substorm intensification, there

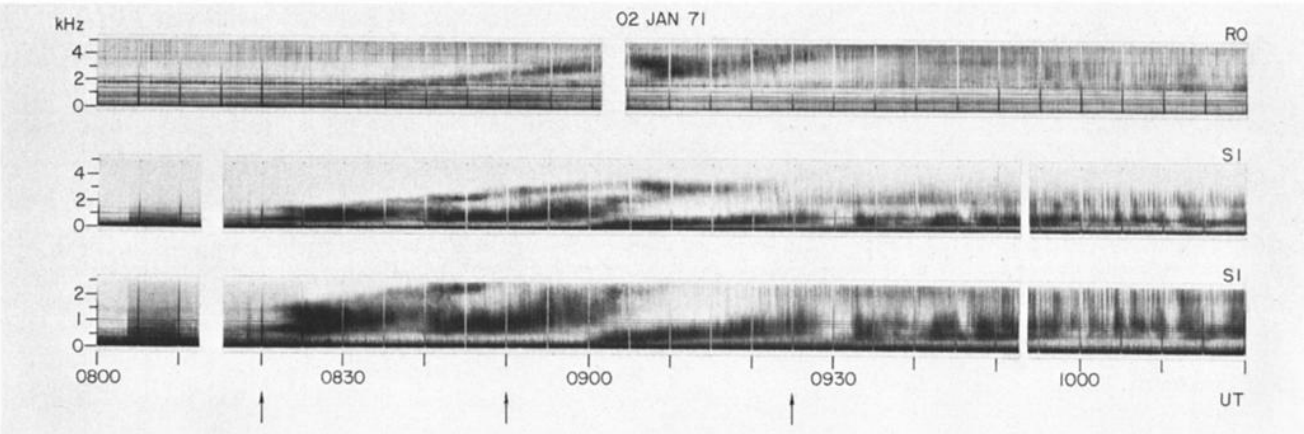

Fig. 7. Broad band VLF spectrum at the Siple (Antarctica) and Roberval (Canada) conjugate pair in the period 0800–1020 UT on January 2, 1971. The top and middle panels compare 0- to 5-kHz frequency time records for Roberval (RO) and Siple (SI). The bottom panel shows the Siple record in the 0- to 2.5-kHz range. Arrows along the time scale indicate the approximate times of substorm intensifications.

was a substantial increase in the intensity of broad band whistlers propagating to Siple through the outer plasmasphere at $L \sim 3.5$–4. Over the period of ~0730–1230 UT, whistler activity in this region was sufficient for measurements of cross-L drifts and hence of the east-west component of the magnetospheric electric field in the region of the whistler ducts. The method used involved measuring whistler travel time at fixed frequencies as described by *Carpenter et al.* [1972].

Figure 2*f* shows the electric field inferred from the whistler data. The curve is a spatial average over results from the two or more paths that could be tracked at a given time in the L range 3.5–4. Fluctuations of the field with period $T \sim 30$ min are resolved. Uncertainty in an instantaneous value of the curve due to experimental error is estimated as ±40% for $|E_w| > 0.25$ mV/m and ±0.1 mV/m for $|E_w| < 0.25$ mV/m. The curve is shown dashed prior to ~0830 UT to indicate greater uncertainty as to details.

As was noted earlier, the plasmapause was determined to be at $L \sim 3.8$ at 0930 UT. An estimate of the probable equatorward displacement of the plasmapause between ~0820 and 0920 UT (when the correlated bursts began) can be obtained from the whistler results on cross-L convection for this interval (prior to ~0930 UT the distribution in space of observed whistler paths was not sufficient for direct identification of the plasmapause). At $L = 4$ the inward equatorial drift associated with an average E_w of ~0.35 mV/m (Figure 2*f*) is ~700 m/s, which transforms to ~55 m/s equatorward at ionospheric heights. In 1 hour the equatorward displacement of the plasmapause near Siple could thus have been roughly 200 km ($\Delta L \sim 0.4$), provided that the equatorial radius of the boundary did not vary by more than ~0.3 R_E within ±15° of the Siple-Roberval meridian (that is, provided azimuthal drift of a plasmapause tilted across L shells did not occur).

The E field curve and ULF power curves (Figure 2) are dissimilar in matters of detail, although they are similar in showing activity increases near 0820 and 0925 UT. The increases in E_w centered at ~1020 and 1110 UT correspond to times of increases in bay activity observed in magnetograms from Great Whale and/or Fort Churchill, stations at auroral latitudes within 1 hour of the meridian of Siple.

DISCUSSION AND CONCLUDING REMARKS

The correlated observations on January 2, 1971, illustrate several ways in which ground-based or balloon observing techniques can be used to investigate magnetospheric processes at subauroral and middle latitudes.

The onsets of the widespread VLF phase anomaly observed within the plasmasphere were coincident with the 0820 UT substorm intensification and particle injection event at synchronous orbit. *Potemra and Rosenberg* [1973] have attributed the phase anomaly to weak precipitation of $E > 40$-keV electrons. However, details of the mechanisms leading to electron precipitation well within the plasmasphere are not yet clear. It is unlikely that electrons injected at 0820 UT would be important in relation to the perturbation onsets. For reasonable values of substorm electric field, particle penetration to $L \sim 3$ within a few minutes would not be expected.

Wave-particle interaction involving ambient trapped electrons is one possible explanation, providing that plasmaspheric noise is enhanced at the times of substorm intensification. In this connection, *Thorne et al.* [1973] have argued that plasmaspheric (ELF) hiss is generated just inside the plasmapause in cyclotron resonant interactions with low-energy electrons and propagates to fill the plasmasphere. They suggest that the hiss could resonate parasitically with energetic electrons, causing precipitation. On the other hand, T. F. Bell (personal communication, 1973) notes that the westward electric field will in principle be accompanied by the lowering of energetic particle mirror points [e.g., *Hines,* 1964] and consequently by particle precipitation. The importance of this process would depend on the intensity of the electric field and the energy density of the energetic electrons involved. For the January 2 event, neither quantity is well known over the longitudinal and latitudinal ranges of the observed phase anomalies. However, other whistler studies have shown that substorm electric fields sometimes penetrate to equatorial distances of at least 2 R_E within the plasmasphere [*Carpenter et al.,* 1972]. In case studies of ionospheric perturbations caused by substorm electric fields it has been found that the effects of only moderately intense substorm activity can be observed as far equatorward as $L \sim 2$ [see *Park and Meng,* 1973]. The phase anomaly appears to be a potentially powerful tool for mapping the occurrence in space and time of low-level precipitation effects within the plasmasphere.

The ULF enhancement near the time of the correlated X ray and VLF bursts is not understood. The correlated bursts exhibited strong periodicities in the period range of 4–12 s [*Foster and Rosenberg,* 1975]. Although it appears that ULF wave activity in this frequency range near $L = 4$ is of magnetospheric origin rather than of ionospheric origin [*Lanzerotti and Fukunishi,* 1974; *Fukunishi,* 1975], the background, more 'noiselike,' ULF perturbations at times could nevertheless result from particle precipitation [*Lanzerotti and Robbins,* 1973; *Fukunishi,* 1975]. The possibility of particle precipitation giving rise to a local source of ULF disturbance in the ionosphere has been discussed earlier by several authors (see review by *Campbell* [1967]). *Bell* [1972] has recently considered this mechanism in the context of VLF wave injection experiments.

The generally larger ULF noise power values for the northern hemisphere stations (Figure 6) is opposite to a statistical study of the conjugacy of ULF power for a January 1972 period found by *Surkan and Lanzerotti* [1974]. The difference may possibly be due to different ionospheric conditions for the various studies. It is hoped that details of ionospheric conditions can be known in greater detail during future campaigns.

A possible explanation of the larger hemispheric difference in the amplitude of the ULF peak at ~0930 UT is the essentially unidirectional (north to south) nature of one-hop whistler propagation along the Siple-Roberval meridian. Particles in cyclotron resonance with these whistlers (and their associated triggered emissions) will tend to be initially traveling northward, and hence higher precipitated fluxes may occur in the north. The precipitating particles may then possibly produce larger perturbing ionospheric effects in the northern hemisphere. Note that this effect may occur even though the natural (atmospheric) loss cone is larger in the south than in the north at this geomagnetic latitude.

The VLF records of Figure 7 show that noise events of the order of 30-min duration and with rising center frequency occurred following several successive substorm intensifications. At these times the ground stations were in the 0300–0400 MLT sector. As *Foster et al.* [1975] point out, the rise in frequency of the noise may be due to a combination of cross-L inward drift of the emitting region and dispersion in the arrival time at the Siple-Roberval meridian of energetic electrons 'injected' near local midnight (assuming a cyclotron resonance interaction process, the more energetic electrons, arriving earlier, would give rise to the lower frequencies). Multiple bands may be the result of the penetration of the magnetospheric path in question by particle 'clouds' with varying prehistories in terms of injection parameters. The propagation of different VLF noise structure on the same magnetospheric path, noted above in connection with Figure 7, has been reported in some detail by *Ho* [1974]. As additional information on the interrelationship of VLF noise bands, electric fields, and particle events is accumulated, it may become possible to use an array of VLF receivers spaced in longitude to indicate the occurrence and subsequent drift and decay of particle clouds.

The rapid increase in the westward electric field near the time of the substorm intensification at 0820 UT, although it is not documented in detail, is consistent with earlier studies of rapid increases in westward electric field at the time of the expansion phase of substorms [*Carpenter and Akasofu,* 1972]. The electric field signature is not of the kind characteristic of an isolated substorm but rather more like that observed during relatively long enduring substorms, when the inward drifts of the plasma persist until near local dawn [*Carpenter et al.,* 1972].

The detection of correlated VLF and X ray bursts appears to require rather special observing conditions. The plasmapause should be slightly equatorward of the station so that the energies and/or fluxes of electrons precipitated through wave-particle interaction processes may be high enough for detection by the balloon technique. If the plasmapause is too far equatorward, X ray levels characteristic of the auroral oval may be present and may obscure any VLF–X ray burst correlations. In these terms, the Siple-Roberval conjugate pair appears to be well located; the L value of the stations (~4) is such that the plasmapause is nearby and subject to transient equatorward displacements during many periods of moderate magnetic disturbance ($3 < Kp < 6$).

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