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Interaction between Whistlers and Quasi-Periodic VLF Emissions

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Quasi-periodic (QP) VLF emissions are noise bursts repeated at intervals of the order of 30 sec. This period is substantially longer than the ~2-sec two-hop whistler mode travel time along the associated magnetospheric field-aligned paths. New details of QP emissions, particularly of interactions between whistlers and QP activity, have been found in a study of VLF recordings from Eights, Antarctica ($L \sim 4$), during the period November 1964 to October 1965. The occurrence statistics show that QP emissions favor the equinoxes, later afternoon hours, and quiet geomagnetic conditions. Emission frequencies generally lie between ~1.5 and 4 kHz. Detailed studies of broad band VLF spectra show that QP emissions are strongly affected by whistlers. Whistlers often disrupt well-behaved QP patterns by suddenly increasing the QP period, by terminating the emission altogether, or by modifying the fine structure of QP bursts (this fine structure frequently consists of periodic VLF emissions and/or VLF chorus elements). Whistlers can sometimes initiate QP emissions by modulating multiphase periodic emissions. When there are strong interactions between QP emissions and whistlers, QP emissions and whistler echo trains have the same time rate of change of upper cutoff frequency. This evidence of complex connections among various types of VLF signals in the magnetosphere adds a new dimension to recent discoveries of transient whistler-induced precipitation of particles into the ionosphere.

A type of VLF radio noise generated in the earth's magnetosphere is observed as a series of bursts with some regularity and relatively long time separation. The bursts are known as quasi-periodic (QP) VLF emissions [*Helliwell*, 1965; *Kimura*, 1967; *Kokubun*, 1971], but they have also been called 'long-period VLF pulsations' [*Carson et al.*, 1965; *Watts et al.*, 1963; *Gallet et al.*, 1963]. Figure 1 is a frequency-time record of a QP emission recorded at Eights station, Antarctica ($L \sim 4$). The top panel shows a long-enduring event with periods in the range of 30–50 sec.

Individual QP bursts may consist of a number of events of shorter duration. These may be 'chorus' elements, or they may be so-called 'periodic emissions,' which repeat at multiples of the two-hop whistler mode travel time. The QP emissions are called discrete or diffuse, depending on whether or not this fine structure is distinguishable. The QP periods are substantially longer than the ~2- to 4-sec two-hop whistler travel time, and they range typically from 10 to 30 sec. Longer periods of up to several minutes have been observed on occasion. The emission intensity usually varies with time, and a QP event may last from a few minutes to a few tens of hours. A typical duration is ~20 min.

The QP emissions were first reported by *Watts et al.* [1963], and a summary of early work on this phenomenon was made by *Helliwell* [1965]. There are at least two general types of QP emissions. One is a low-frequency type, with center frequency near 1 kHz, that is observed most commonly at relatively high latitudes, near $L = 7$, and is accompanied by micropulsation activity [*Kitamura et al.*, 1968, 1969; *Carson et al.*, 1965]. The other type, the kind discussed in the present paper, tends to be observed near $L = 4$ and exhibits a higher center frequency, usually in the range of ~1–6 kHz. *Kitamura et al.* [1968, 1969] found that this type of QP emission is not correlated in any clear way with micropulsations, and their observation was confirmed by the present research.

Carson et al. [1965] showed that the QP emission period tends to increase with increasing observing latitude, and it was found in the present study that the emission frequency tends to decrease with increasing observing latitude (see next section).

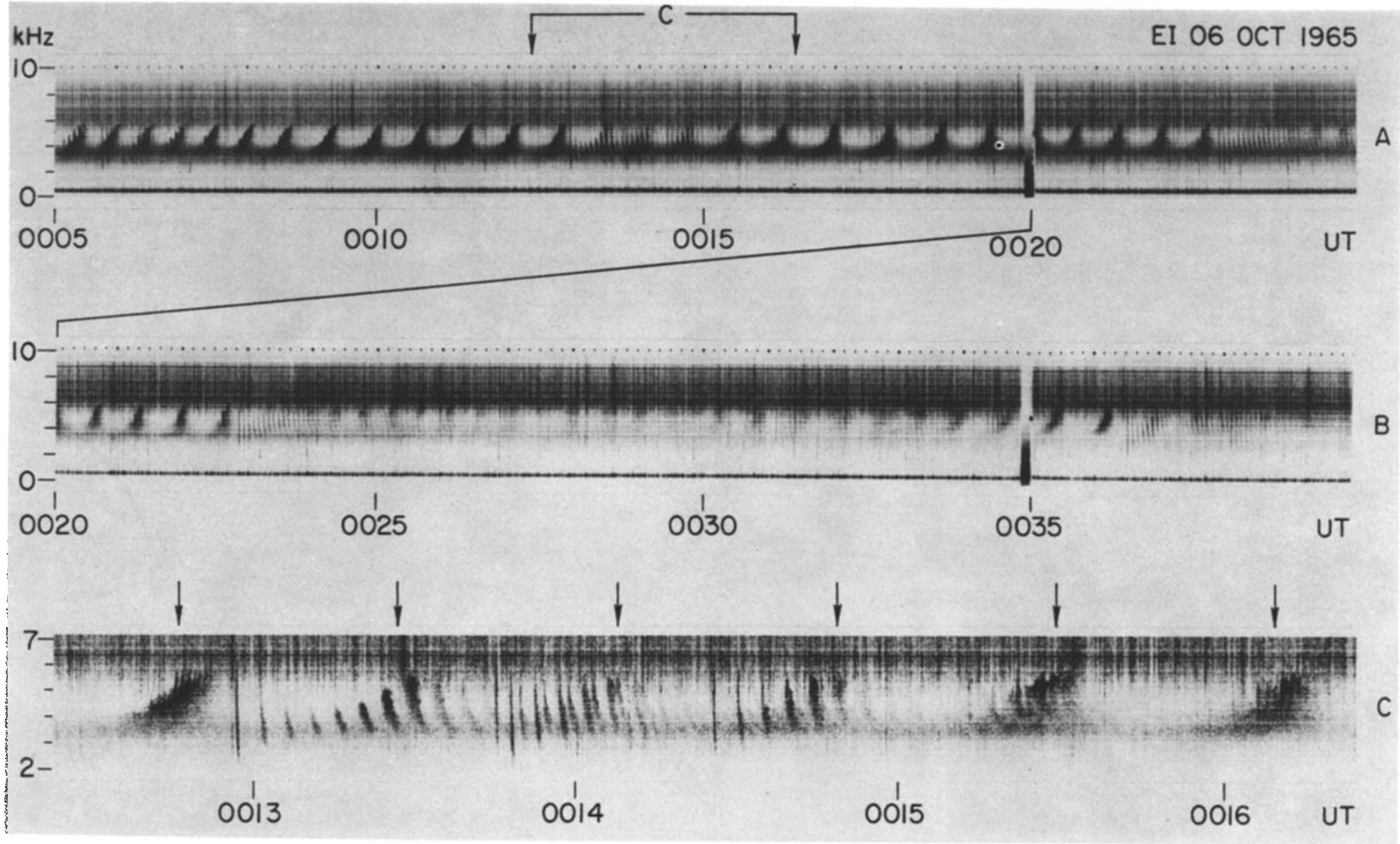

Fig. 1. Frequency-time records illustrating the interruption and suppression of QP emission activity by whistlers. A whistler echo train near 0013 UT interrupted the QP activity for a period of several minutes. The whistler event near 0023 suppressed well-defined QP activity for a period of about 10 min. A whistler near 0036 effectively terminated the QP activity in this observing period. The dots near 10 kHz are time marks at 10-sec intervals, and the data gaps near 0020 and 0035 UT are due to routine calibration of equipment. The recordings were made at Eights, Antarctica ($L \sim 4$).

The present study presents evidence of strong interactions between QP emissions and whistlers. Such effects were first pointed out to the author by J. P. Katsufrakis. An example is shown in Figure 1 near the right end of panel A and is repeated in panel B at the left. QP emissions are apparently suppressed by a strong whistler echo train. Then the emissions manage to recover and reappear on the right-hand side of panel B. However, another strong whistler echo train comes in near 0036 UT and terminates the entire event. Panel C is an expanded version of the portion marked C on panel A. The modification of the QP spectra by whistlers is evident. Further details of this event will be described later in this paper.

Modifications of QP characteristics by whistler signals are of particular interest in view of increasing experimental evidence for strong wave-particle interactions in the magnetosphere. For example, *Rosenberg et al.* [1971] reported that VLF waves induce precipitation of energetic electrons ($E > 30$ kev) observed by means of balloon-borne X ray detectors. *Helliwell et al.* [1973] report that the amplitude of long-distance subionospheric VLF transmissions may be modulated by whistlers, evidently as a result of perturbations of the lower ionosphere caused by whistler-induced precipitation of energetic electrons. It seems possible that these phenomena are related to the whistler-induced modifications of the QP emissions reported here.

Occurrence of QP Emissions

Narrow band VLF amplitude charts from Eights station, Antarctica (75°S, 77°W geographic; $L = 3.9$), covering the frequency range 0.5–12 kHz were examined for QP emissions during the period November 1964 to October 1965. Identified were 46 QP events, ranging in duration from a few minutes to a few tens of hours. Of the 46 events, 19 events representing 11 days were selected for detailed study using frequency-time spectrograms of broad band (0–10 kHz) tape recordings. The time of occurrence and the emission frequency range of these 19 events are listed in Table 1.

Figure 2 summarizes the occurrence statistics of QP emission events between November 1964 and October 1965. Figure 2*a* is a histogram of the number of events during each month, and Figure 2*b* is a histogram of the number of days on which events were observed. Both distributions show peaks near the equinoxes. Similar results were found by *Kitamura et al.* [1969]. In October 1965, data were available only through October 13, and the normalized data for the month are shown dashed.

Figure 3 shows the distribution of QP emission frequencies for the 19 selected events listed in Table 1. Each horizontal bar shows the range

TABLE 1. Time and Frequency Range of QP Emission Events

Event	Date, 1965	Time, UT	Frequency Range, kHz
1	March 25	1726–1735	1.0–2.0
2	March 26	1420–1605	1.2–2.0
3	April 1	1925–1935	2.25–3.5
4	April 1	2050–2115	2.0–4.0
5	April 9	0314–0321	4.0–5.0
6	April 10	1509–1515	1.50–4.0
7	April 10	2058–2105	1.75–3.5
8	April 10	2107–2122	1.75–3.25
9	April 10	2137–2155	1.75–3.5
10	April 10	2159–2220	2.0–4.0
11	April 20	1540–1600	2.0–3.0
12	April 21–22	2330–0028	2.5–3.5
13	April 22	0122–0143	2.5–3.5
14	April 22	0303–0312	2.5–4.0
15	October 4	0510–0642	1.75–3.75
16	October 4	0650–0656	1.75–2.5
17	October 4	0704–0712	1.75–3.75
18	October 5	0040–0250	1.7–3.5
19	October 5–6	2320–0023	3.0–6.0

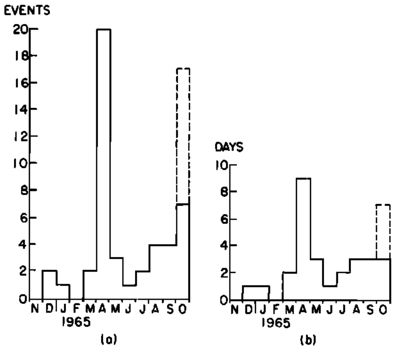

Fig. 2. Histograms of QP emission activity at Eights station during the period November 1964 to October 1965. (*a*) Number of QP events during each month. (*b*) Number of days on which QP emissions were observed. Observations were discontinued on October 14, 1965, and the normalized data for October are shown dashed.

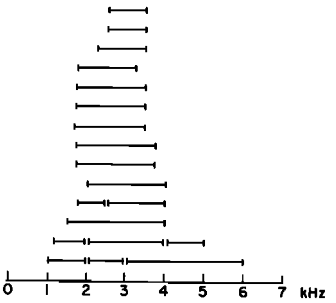

Fig. 3. Distribution of QP emission frequency for 19 events selected for detailed studies of broad band spectra (see text). Each bar represents the range of emission frequency observed during an event. All 19 events occurred between March and October 1965.

of emission frequency during an event. The distribution is sharply peaked near 3 kHz, with only two events falling outside the 1- to 4-kHz range. *Kitamura et al.* [1969] reported that at Byrd station, Antarctica ($L = 6.8$), QP emission frequencies were generally less than 1 kHz. This result suggests that there may be a systematic variation in QP emission frequency with geomagnetic latitude. A latitude dependence of the QP emission period has been reported by *Carson et al.* [1965].

The diurnal variation of QP emission activity is illustrated in Figures 4 and 5. Figure 4 is a histogram of the number of events, and Figure 5 shows the total duration in minutes of QP emissions; both are plotted against UT and geomagnetic local time (GLT) at Eights. All 46 cases were included. The highest probability of observing QP emissions occurs in the late afternoon hours. Although the total duration of 300 min for 1400–1500 GLT was only ~1.5% of the total observing time over 350 days, the percentage occurrence at 1400–1500 GLT within a month of the equinoxes was about 6%.

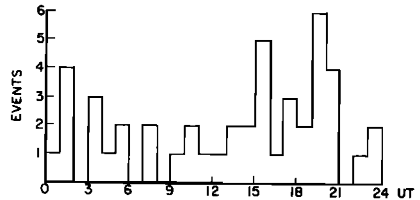

Fig. 4. Diurnal variation of QP emission activity at Eights during the period November 1964 to October 1965. Number of events observed is plotted against UT and GLT.

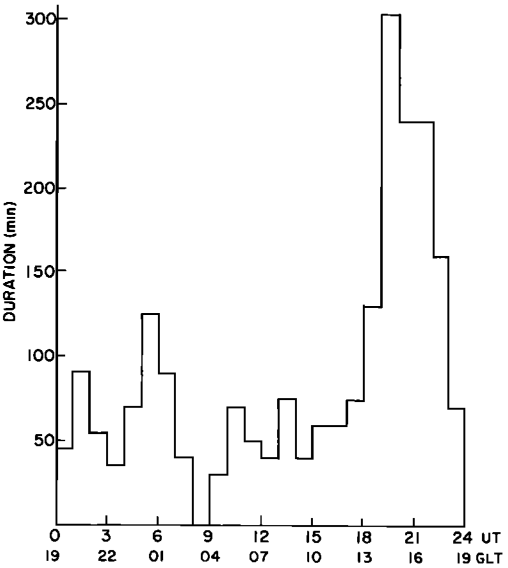

Fig. 5. Total duration in minutes of QP events observed at Eights during the period November 1964 to October 1965 plotted against UT and GLT.

Figure 6 shows the distribution of QP emission events according to the 3-hour planetary magnetic activity index *Kp*. The shaded area represents the 19 events selected for detailed spectral analysis and listed in Table 1. Evidently, the emissions tended to occur under relatively quiet conditions ($Kp \leq 2$). However, many of the cases were found to be preceded within ~12 hours by higher levels of disturbance activity.

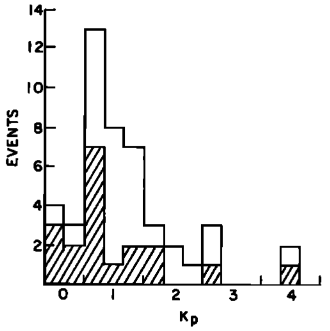

Fig. 6. Distribution of QP events observed at Eights according to the 3-hour *Kp* index. The crosshatched portion represents the 19 selected cases of Figure 3.

CORRELATIONS WITH WHISTLERS

In nearly all the cases of QP emissions, whistlers were also detected on the spectrographic records. In many cases there was clear evidence of whistler propagation along the path followed by the emissions. This relationship was established through detailed comparison of the dispersion characteristics of particular whistler components and of individual elements of the QP emissions. In most cases the emission-whistler path was between $L \sim 3.5$ and 4.5 and was within the plasmasphere (detailed relationships between QP emission path location and the plasmapause have not yet been determined).

In this section we present examples of strong interactions between QP emissions and whistlers. The interaction may take a variety of forms involving emission period, upper cutoff frequency, etc., as described in detail below. In all the cases studied to date, strong interactions seem to occur only when either the whistler noise frequency lies within the QP emission band or the whistler has strong and long-enduring echoes in the emission band.

Emission period. In the absence of identifiable discrete emission components, it is difficult to define and measure the period of QP emissions accurately. In such cases the period is measured from the strongest part of the emissions, i.e., the darkest part of the frequency-time spectrograms and/or the amplitude peak of amplitude-time records. The period measured this way is affected by changes in amplitude characteristics within each QP emission, but this effect is relatively small in comparison with changes in period associated with whistlers.

Figure 7 shows a 'multiphase' emission event that occurred on April 22, 1965. (As is noted above, QP emissions frequently consist of a series or train of discrete 'periodic' emissions separated from one another by the ~2- to 4-sec two-hop whistler mode travel time along the associated magnetospheric path [*Brice*, 1965]. Frequently, more than one series of periodic emissions propagates along the same path, phased so that the interval between successive emissions recorded on the ground is less than the two-hop whistler mode delay: hence the term 'multiphase' emission.) The purpose of Figure 7 is to show how the QP emission period is lengthened by whistlers. The portions of panel A marked B, C, D, and E are shown below panel A on an expanded time scale. Panel B shows a relatively undisturbed interval in which the QP period is about 35 sec and is fairly regular. The effects of whistlers are illustrated in panels C, D, and E, which have been arranged so that the emissions second from the left are approximately aligned with the emission at ~00h 07m 25s on panel B. In panels C, D, and E the next QP emission occurs after an interval significantly longer than the 35-sec interval in panel B. This effect is particularly well defined in panels C and E. In panel C a whistler with succeeding echoes at ~00h 09m 45s interrupts a period of well-behaved QP emissions, and the QP period increases by roughly 15 sec. A dramatic interruption is shown near 0015 UT in panels A and E. The time until reoccurrence of the QP emission is nearly 60 sec. Generally, during the event illustrated in Figure 7, it was found that QP emissions tended to return to their regular period during intervals free from well-defined whistler activity.

Similar behavior was observed during events 2 and 15 of Table 1. When the QP emission period was affected by whistlers, it was always increased. No case has yet been found in which the QP period was shortened by whistlers.

Similar lengthening of the QP period has been observed for periodic emissions, when, for example, one of the elements or phases of the emission activity becomes exceptionally strong and gives rise to an interruption in the normal QP periodicity [*Ho*, 1972].

Suppression and initiation of emissions. Whistlers can suppress QP emissions for one or more emission periods, as is shown above in connection with Figure 1. Dots near 10 kHz in Figure 1 are time marks at 10-sec intervals, and data gaps occur for approximately 10 sec during calibration at 0020 and 0035 UT. In panel B of Figure 1 a long-enduring whistler echo train starts at 00h 22m 50s UT, and QP emissions are suppressed until ~0033 UT. Then the emissions grow in intensity and appear to be fully recovered by ~0036 UT, but another strong whistler train starts at 00h 36m 30s UT and terminates the emission event.

The segment marked C in panel A is shown in the bottom panel on an expanded time scale. A whistler echo train at about 0013 UT appears

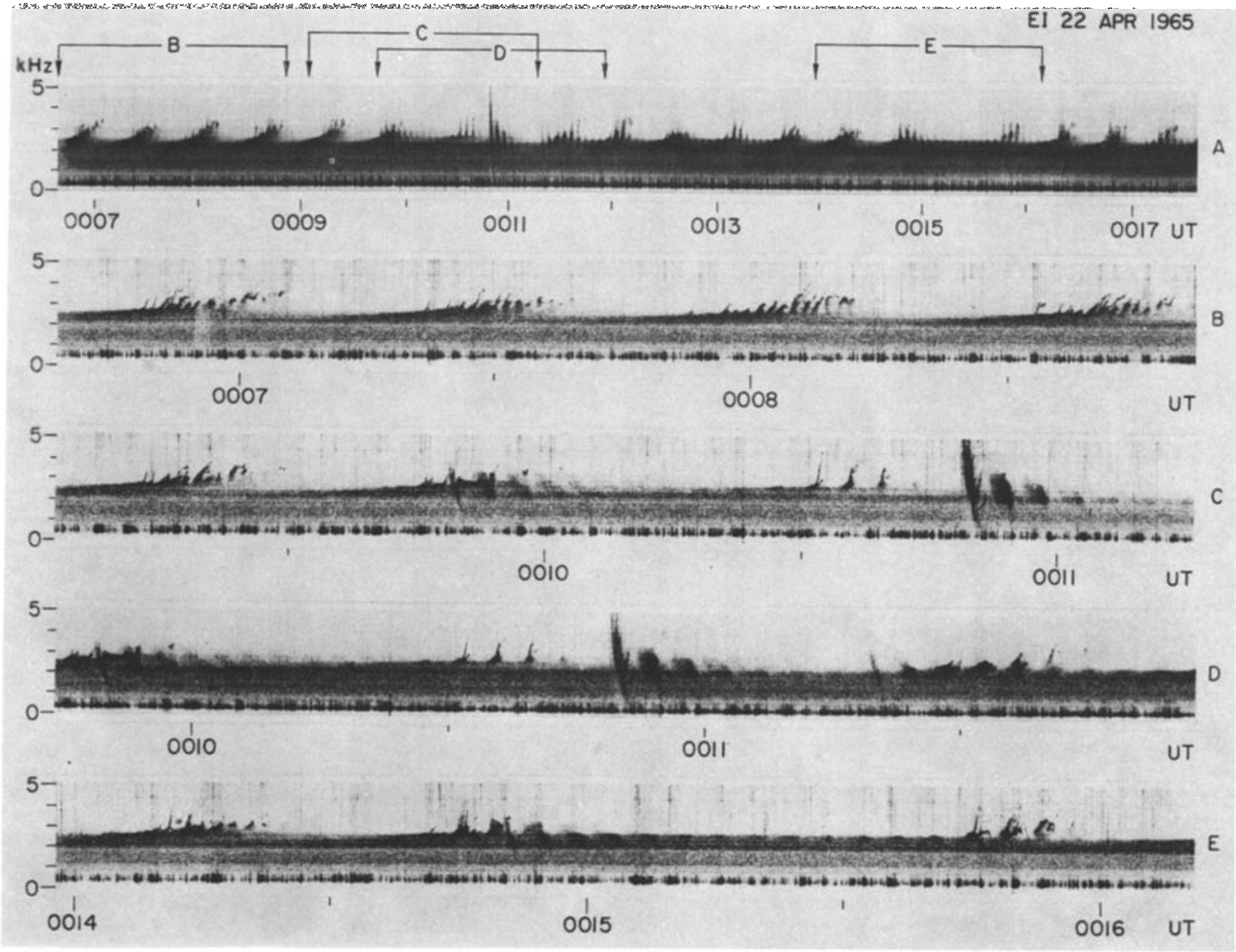

Fig. 7. Frequency-time spectrograms showing an example of discrete QP emissions and the effects of whistlers on QP spectra. Portions of panel A are shown in panels B, C, D, and E on an expanded time scale. Panel B shows QP emissions consisting of multiphase periodic emissions. In panels C, D, and E, whistlers and their echoes temporarily increase the QP period and reduce the number of phases in the periodic emissions (see text).

to suppress the QP emissions. When the emission returns near 00h 15m 30s, its previous period and phase are preserved, as is indicated by the arrows above the panel.

The disruptive effect of a whistler on existing emission activity has its converse in that a whistler may appear to give rise to a QP emission. Figure 8 shows a long train of regular periodic emissions with complex irregular risers (>2.5 kHz) on top of the emission band (four 'phases' are detectable). The sequence is interrupted by a relatively strong whistler near 2058 UT, after which there is an alteration in intensity of the emissions, so that the activity begins to separate itself into recognizable QP emissions with periods of about 25 sec.

Upper cutoff frequency. QP emissions in general have a tendency to rise in frequency (see, for example, Figures 1, 7, and 9). When whistler echo trains occur during a QP emission event, the rising upper cutoff frequencies of emissions and whistler echo trains show the same slope. This observation is illustrated in Figure 9 by examples from a long-enduring QP emission event of October 5–6, 1965. In the top panel, QP emissions show little change in frequency, and the long whistler echo train starting at ~2330 UT shows no systematic change in upper cutoff frequency. The whistlers, however, appear to cause some disorder in the periodicity of the QP emissions. About 20 min later, QP emissions show rising tones at the rate of ~50 Hz/sec, as is shown in panel B. The upper cutoff frequency of the whistler echo train starting at ~23h 49m 15s UT rises in the manner of the QP emission component immediately preceding the whistler. The rate of increase of upper cutoff frequency of the whistler train and of the QP emission is the same within measurement errors. Still later in the same event, panel C shows an emission with steeper slope, ~140 Hz/sec. The upper cutoff frequency of the whistler echoes again follows the pattern of the emissions.

Figure 10 shows changes in the slope of the upper cutoff frequency for 1 hour during the event of Figure 9. Open circles are used for QP emissions, and crosses for whistler echo trains. A close agreement between them is evident.

Phase of discrete QP emissions. QP emissions often consist of multiphase discrete emissions. Figure 7 shows examples of such emis-

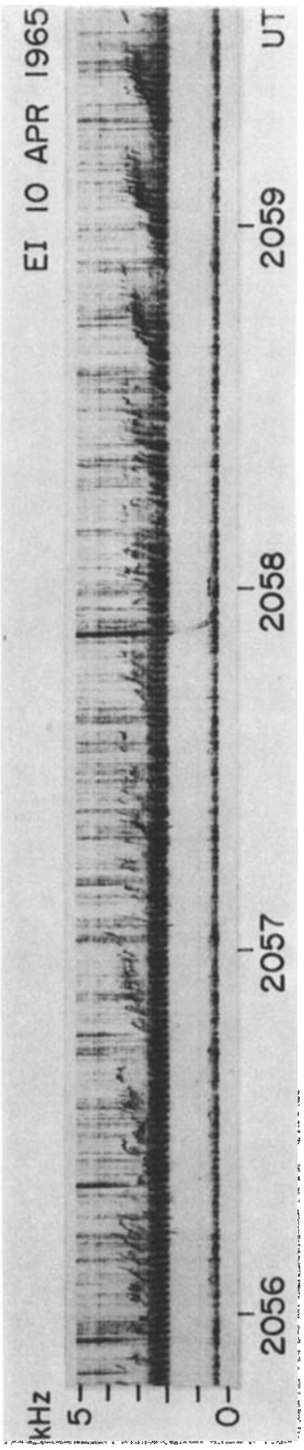

Fig. 8. An example of the apparent initiation of QP emissions by a whistler. Following the strong whistler near 2058 UT, long-enduring multiphase periodic emission activity is modulated so as to appear in QP emission form (see text).

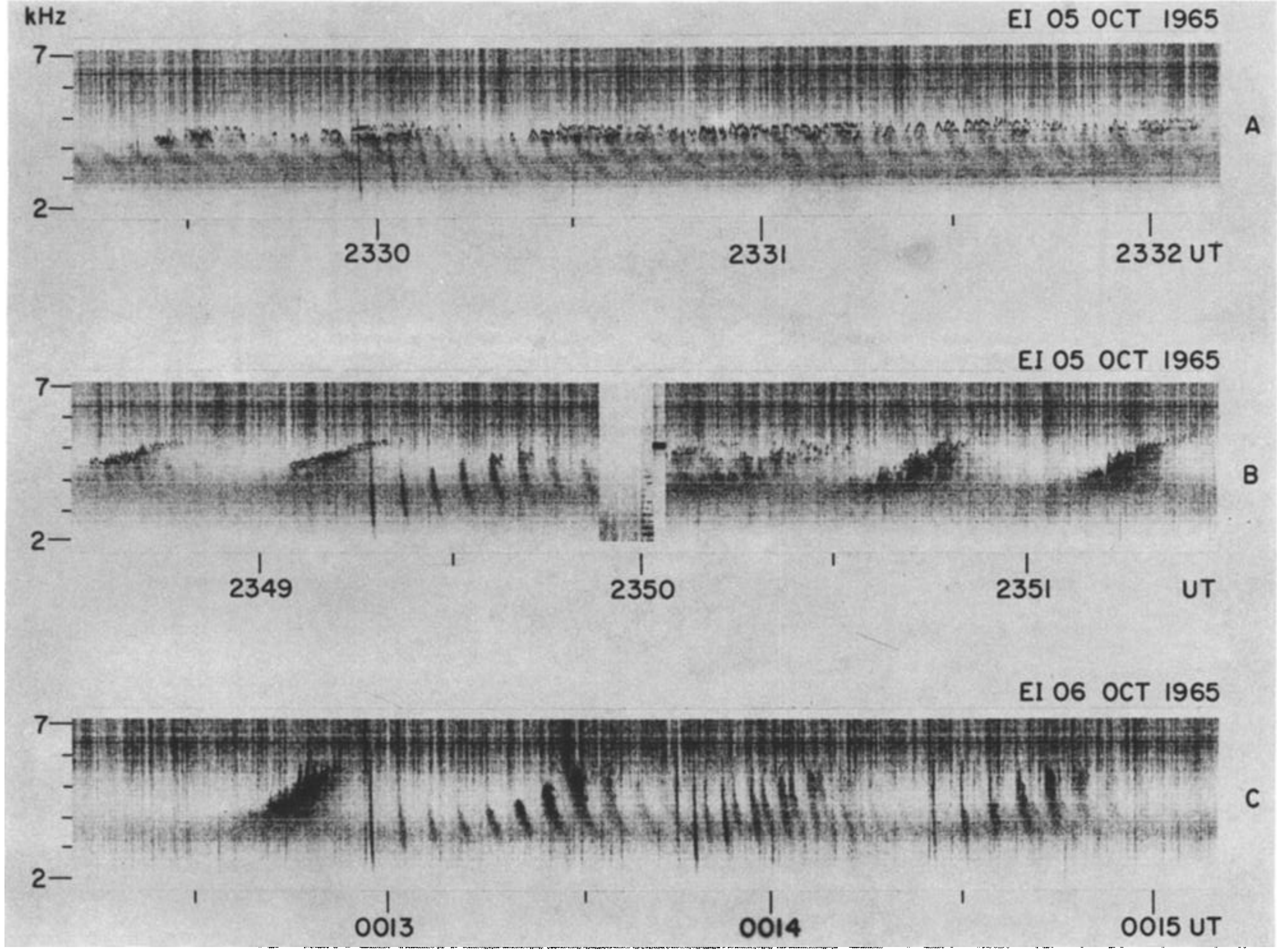

Fig. 9. Frequency-time records showing similarity between the upper cutoff frequency characteristics of QP emissions and of whistler echo trains. The three panels represent recordings within a 1-hour period at Eights, Antarctica.

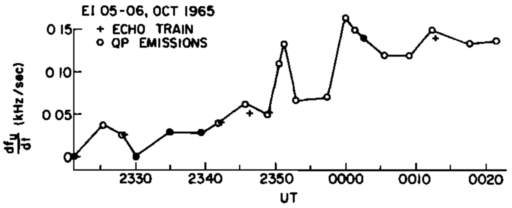

Fig. 10. Graph showing the variation within a 1-hour period of the time rate of change of the upper cutoff frequency of QP emissions and of whistler echo trains. The observing period is the one illustrated in Figure 9. Measurement errors are estimated to be less than 0.0125 kHz/sec.

sions; the details are best seen in panel B. When whistlers interrupt QP emissions, as is shown in panels C, D, and E, the emissions immediately following the whistlers show only one phase. For example, in panel C the first emission is a multiphase emission as is the one in panel B, but in the third emission, following the interruption by the whistler echo train at ~0010 UT, only one phase is seen. Three risers starting at 00h 10m 30s UT are separated by the two-hop delay of the preceding whistler echo train, and they are in phase with the whistler echoes (i.e., they occur when whistler echoes are expected). The same behavior is observed in panels D and E. It thus appears that whistlers may suppress emission components that are out of phase with whistler echoes and allow only in-phase components to be excited.

CONCLUDING REMARKS

Whistler signals entering the magnetosphere can evidently perturb the magnetospheric particle population so as to produce a variety of measurable effects, including particle precipitation into the lower ionosphere (for example, *Rosenberg et al.* [1971] and *Helliwell et al.* [1973]). These reported precipitation effects are relatively brief in duration, involving, for example, bursts of X rays correlated with bursts of VLF chorus [*Rosenberg et al.*, 1971]. Perturbations of the low-latitude ionosphere by whistler-induced precipitation have been reported by *Helliwell et al.* [1973]. These involve changes in amplitude of subionospherically propagating VLF waves. The perturbations develop within a few seconds and decay over periods of the order of 30 sec.

The present research, instead of revealing precipitation effects, shows changes in the VLF output of a complex amplifying echoing magnetospheric path system. A perturbing whistler interferes with a long-enduring process that may be underway for an interval of the order of 1 hour and that, when it is interrupted, may require several minutes to recover. Because of the long-enduring nature of the QP process its perturbation by entering waves seems a particularly attractive subject for study using man-made transmissions. It is hoped that the VLF transmitter experiment being established at Siple, Antarctica, may be used to explore the details of the natural phenomena reported here.

It was found in the present research and reported by *Ho* [1972] that, even in the absence of perturbing whistlers, there may be significant, generally more gradual, changes with time in QP emission activity. These changes may be associated with changes in the properties of discrete emissions and possibly with the propagation of VLF hiss. In further studies it is hoped that more will be learned about the detailed evolution of QP events with time, both under the influence of internal magnetospheric processes and of perturbing whistlers and man-made signals.

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