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An Investigation of Quasi-Periodic VLF Emissions

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Quasi-periodic VLF emissions (QP's) observed at Eights, Byrd, and Polar Plateau Stations in Antarctica have been investigated. Periods of most QP's range from about 10 sec to about 2 min. At each of the stations QP's were generally found when the observing station was on the daylight side of the earth. Two general types of QP's can be identified on the basis of spectral structure and associated geomagnetic micropulsation (GP) activity. One type, which is characterized by an emission frequency that increases without interruption during one quasi-period, lacks association with GP activity. When this type of QP occurs, either there is no concurrent GP activity or the QP period is entirely different from that of the accompanying GP. The VLF emissions may be either diffuse or discrete or a combination of both. The period often varies with the average VLF signal strength, becoming longer for weaker emissions. The second type of QP exhibits an association with GP activity. The upper frequency limit of the emission band often fluctuates in synchronism with changes in the signal strength. This type of QP has a diffuse spectral structure and is referred to here as low-frequency hiss. Such QP's often occur simultaneously with chorus and/or periodic emissions that may or may not show QP variations. Quasi-periodic low frequency hiss associated with geomagnetic micropulsations does not generally occur simultaneously at a pair of magneto-conjugate stations. QP's of the second type have lower emission frequencies (0.3–1.5 kHz) than the first type (1.5–6 kHz).

INTRODUCTION

VLF emissions whose signal strength changes in time with fairly regular periods different from, and generally longer than, the two-hop whistler group delay are called quasi-periodic (QP) VLF emissions [*Helliwell,* 1965] or long-period VLF pulsations [*Carson et al.,* 1965]. *Gustafsson et al.* [1960] and *Aarons et al.* [1960] observed at Kiruna quasi-periodic changes in VLF emissions centered at a frequency of 750 Hz and pointed out their possible correlation with geomagnetic micropulsation (GP) activty. (Table 1 gives the locations of stations mentioned in this paper.) *Egeland et al.* [1965] found that such VLF emissions at Kiruna have maximum signal strength at a frequency around 700 Hz with an emission bandwidth of about 500 Hz. They also found that the signal strength of such VLF emissions often changes in time with a period of 20–30 sec accompanying geomagnetic micropulsations with approximately the same period and an amplitude of a few gammas.

We have investigated QP's observed by the Stanford University VLF group at three Antarctic stations. About 400 QP events recorded on strip charts and dynamic spectra for some selected QP events have been studied. Many examples of the simultaneous occurrence of QP's and GP's were found. In some of these events, the periods of QP's and GP's were close enough to suggest an association between the

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TABLE 1. Locations of Stations Referred to in This Paper

Station	Geographic Coordinates		Geomagnetic Coordinates	
Kiruna	67.8°N	20.4°E	65.3°N	115.5°
Great Whale River	55°17'N	77°46'W	67.8°N	350.0°
Eights	75°23'S	77°17'W	63.8°S	355.3°
Polar Plateau	79°15'S	40°30'E	77.2°S	52.5°
Byrd	79°59'S	120°01'W	70.6°S	336.0°

two phenomena. In other events, however, the QP's occur, either with no concurrent GP activity, or with GP activity whose period is greatly different from the QP period. In this paper we describe those characteristics of GP-associated QP's that distinguish them from QP's that exhibit no relationship with GP activity.

QP's and GP's Recorded on Chart at Byrd Station

Charts obtained during the six equinox months, February to April and September to November 1964 have been examined. These particular times were chosen because QP activity at Byrd has been found to be greater around the equinoxes than during either summer or winter. VLF emission signal strengths in three filtered frequency bands, centered at 0.4, 1.4, and 8 kHz, respectively, were recorded on strip chart. GP activity in one component (geographic north-south) over a rather broad frequency band (0.02–5 Hz) was recorded on the same chart.

QP's were observed in the frequency bands centered at 0.4 kHz and 1.4 kHz, but not always simultaneously. No QP event was observed in the band at 8 kHz. The periods of most QP's observed range from 10 sec, the minimum period resolvable on the charts, to 2 min. QP's with longer periods, up to about 10 min occur occasionally. The durations of the QP's range from a few min to several hours but are usually of the order of several tens of min. For the six equinox months studied, the occurrence of QP's averaged a few tens of events each month. During the months of February to April 1964, 205 QP events were observed, whereas 171 events were found from September to November. Most QP's appear when the observing station is on the daylight side of the earth (Figure 1).

Relationship between QP's and GP's

When both VLF emissions and GP activity are initially low, VLF emission activity often remains low even when GP activity is suddenly enhanced. The converse is also true, i.e. GP activity often remains low even when VLF emission activity is enhanced abruptly. Thus GP's and VLF emissions seem to be generated by different mechanisms. However, some QP events take place with concurrent GP activity. In such a QP event, the period of the QP and that of the simultaneous GP are not necessarily the same. Figure 2 shows the occurrence frequency of QP's and simultaneous GP's as a function of their periods. The periods of most QP's are seen to lie in the range from 20 to 30 sec, which is also the period of most of the simultaneous GP's. In this paper, QP's with simultaneous GP's whose periods are the same to within about 25% will be called GP-associated QP's. Figure 5 (which will be discussed later) shows an example of a GP-associated QP event. GP-QP association is most clear in the time intervals 1230–1235 UT and 1237–1240 UT. Even during these time intervals, however, no clear peak-to-peak correspondence can be seen between the GP and QP curves. The difference between the average QP period and that of the corresponding GP is about 10% in the first time interval and about 20% in the second.

Before the onset of a GP-associated QP event, VLF emission activity is normally already occurring. Such prior activity is seen very clearly in the example shown in the bottom half of Figure 3. Before 1503 UT the VLF activity consists of nondiscrete noise and closely spaced risers shown on the spectrum sample at 1450 UT in the middle of Figure 3. The onset of GP oscillations coincides with the beginning of QP variations in the noise, shown on the chart at the bottom of the illustration and

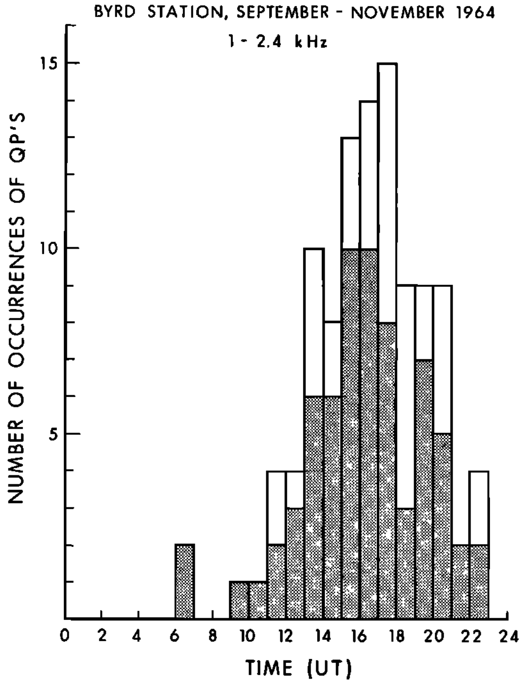

Fig. 1*a*.

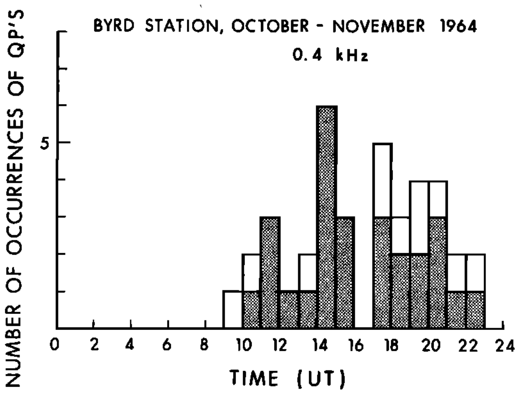

Fig. 1*b*.

Figures 1*a* and *b* show the diurnal variation of occurrence of QP's observed from September to November 1964 at Byrd Station through filters at (*a*) 1–2.4 kHz and (*b*) 0.4 kHz. The dotted portion of the figure represents GP associated QP's and the clear portion nonassociated QP's. Local midnight is 0800 UT and magnetic midnight approximately 0400 UT. The diurnal variation of occurrence from February to April is similar.

on the 1550 UT spectrum sample. Also, typical of QP events, the minimum VLF signal level during each pulsation does not reach zero on the chart as exemplified in the same figure. GP-associate QP's therefore have the appearance of a modulation, with a GP period, of a pre-existing VLF emission 'carrier' signal.

Figure 4 shows an association between GP's and VLF emissions that appears to be of a

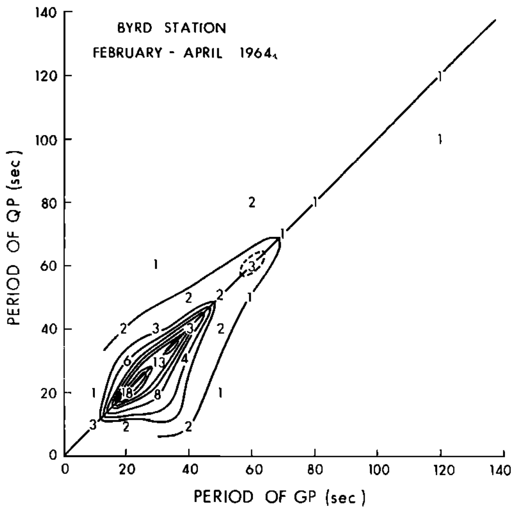

Fig. 2*a*.

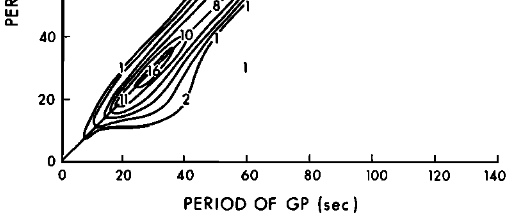

Fig. 2*b*.

Figures 2*a* and *b* show a three-dimensional plot of the occurrence of simultaneous QP's and GP's at Byrd Station as a function of their periods (*a*) February to April 1964 (*b*) September to November 1964. The numbers on the plot give the number of cases with the combination of periods of QP's and GP's represented by the placement of the numbers. Occurrence contours have been sketched in.

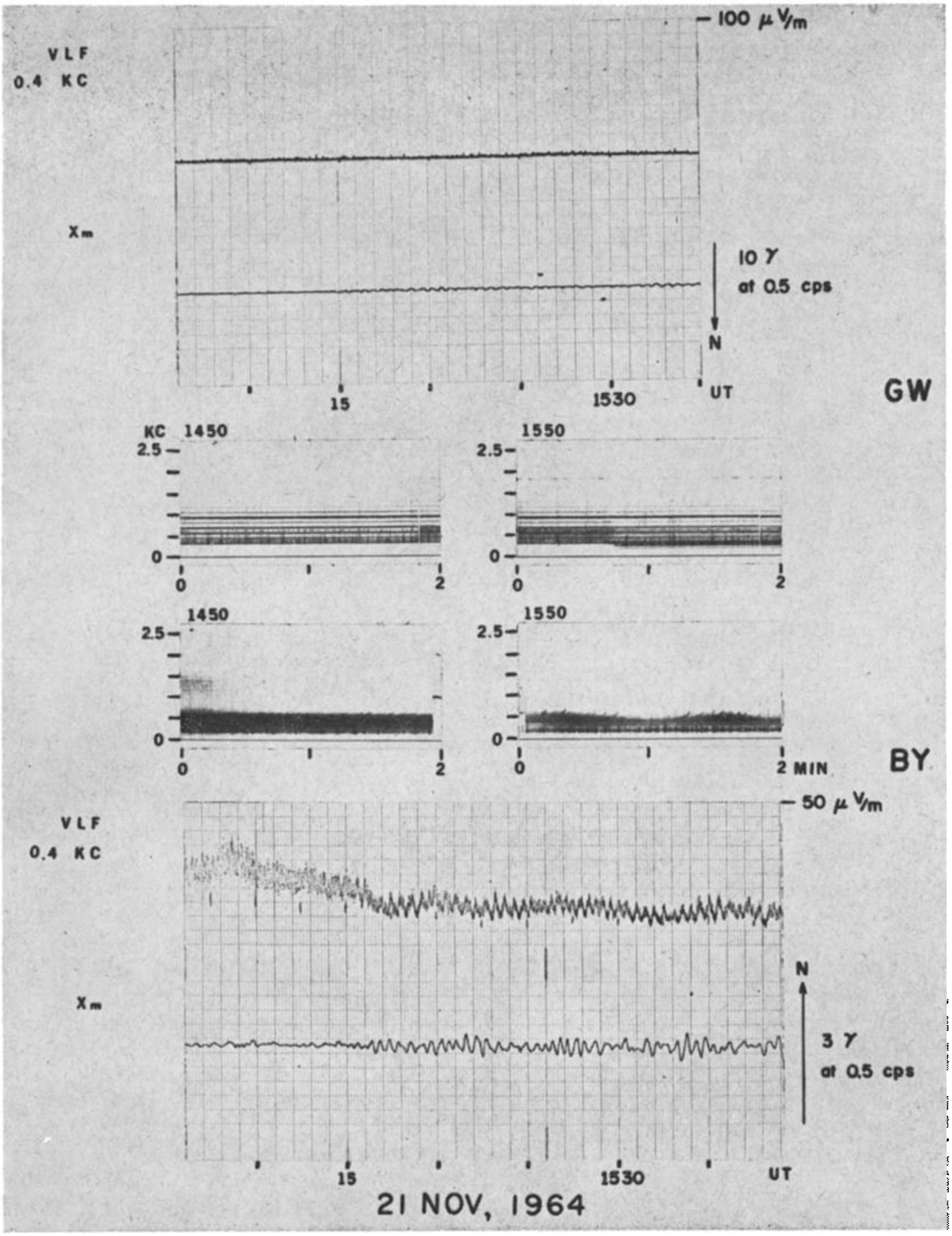

Fig. 3. A GP-associated QP event observed at Byrd Station (BY). The VLF emission activity at Great Whale River (GW), magnetically conjugate to Byrd, is very weak.

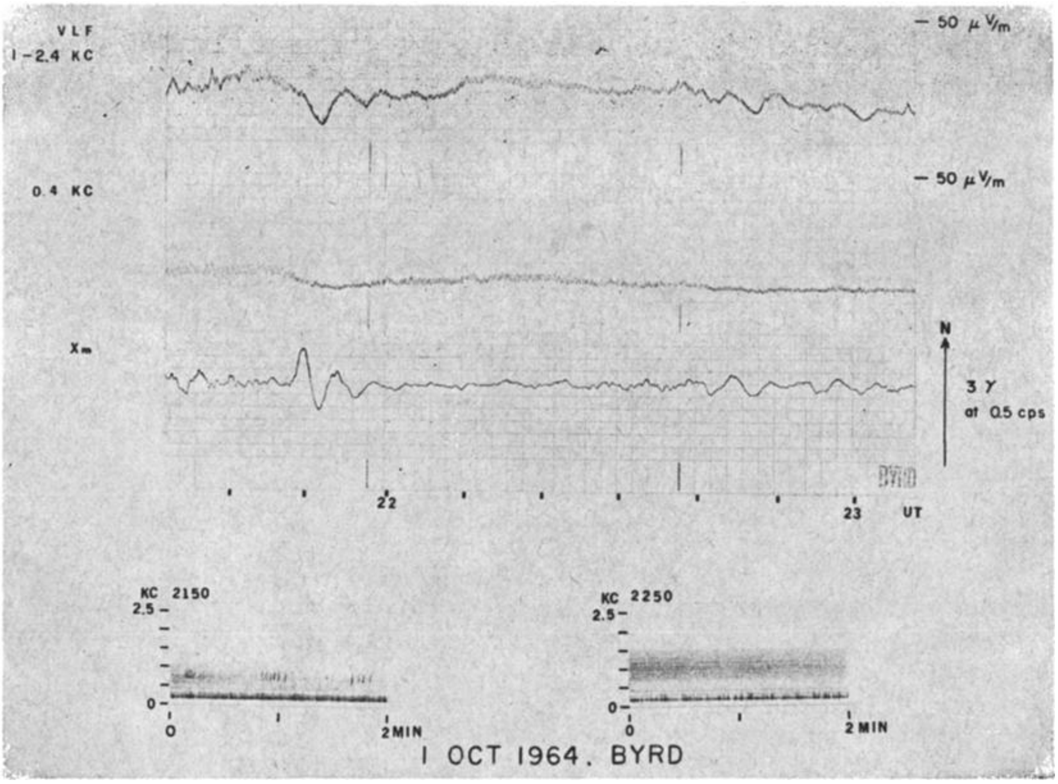

Fig. 4. An example of a GP-associated QP event. The QP takes place in the frequency channel 1–2.4 kHz but not in that at 0.4 kHz. The average VLF emission level in both channels is decreased at the onset of the long-period GP.

different type. The period is comparatively long and irregular. Two events are seen, beginning at 2150 and 2240 UT, respectively. They appear both on the X_m and 1–2.4 kHz channels and last only a few cycles. The average level of the VLF activity is also reduced on both the 1–2.4 kHz channels during the periods of GP activity. The concurrence of QP's and the decrease of VLF level suggests that this type of activity is caused by a particle event, which, in turn, causes ionospheric absorption and magnetic field variations. Relationships between particle events and micropulsations have been investigated by *McPherron et al.* [1968].

Spectral Structure of QP's

The spectrograms of twenty-two events listed in Table 2 were reproduced from tape records obtained at three stations in Antarctica, Byrd, Eights, and Polar Plateau. Of the total of twenty-two QP events, seven (numbers 3, 4, 5, 7, 8, 9, and 22) were found to be associated with GP activity and ten (numbers 1, 2, 12, 13, 14, 17, 18, 19, 20, and 21) not to correspond to GP activity. For the remaining five events, it is difficult to decide whether there is any associated GP activity or not.

Most of the GP-associated QP's are taken from Byrd Station records, whereas most of the nonassociated QP's are from Eights Station. This bias is unintentional, and many cases of both types are found in the records of both stations. However, the spectrograms of GP-associated QP's from Eights Station were more difficult to analyze because of the brevity of the samples and the confusing amount of simultaneous activity.

GP-Associated QP's

In every one of the GP-associated QP events the QP variations occurred in a diffuse, low-frequency (0.3–1.5 kHz) broadband noise, which

TABLE 2. Quasi-Periodic VLF Emission Events Recorded on Tape

Event	Date	Station	Time Interval of Observation, UT
1	May 10, 1964	BY	1000–1005
2	June 6, 1964	BY	1930–1935
3	Sept. 7, 1964	BY	1250–1300
4	Oct. 1, 1964	BY	2150–2152
5	Oct. 7, 1964	BY	1850–1852
6	Oct. 26, 1964	BY	1720–1735
7	Nov. 21, 1964	BY	1550–1552
8	Dec. 8, 1964	BY	2150–2151, 2205–2206, 2220–2221, 2235–2236, 2250–2251.
9	Feb. 25, 1965	BY	2005–2006, 2020–2021, 2035–2036, 2050–2051.
10	March 4, 1965	EI	1635–1805
11	March 25, 1965	EI	1735–2020
12	April 23, 1965	EI	0135–0205
13	May 6, 1965	EI	1939–2150
14	July 13, 1965	EI	2258–2350
15	July 22, 1965	EI	1310–1600
16	Sept. 2, 1965	EI	2122–2300
17	Sept. 9, 1965	EI	1902–1930
18	Oct. 5, 1965	EI	0022–0342
19	Oct. 5, 1965	EI	0416–0734
20	Oct. 5, 1965	EI	2320–0145
21	March 29, 1966	PP	1620–1625
22	July 16, 1966	PP	1215–1235

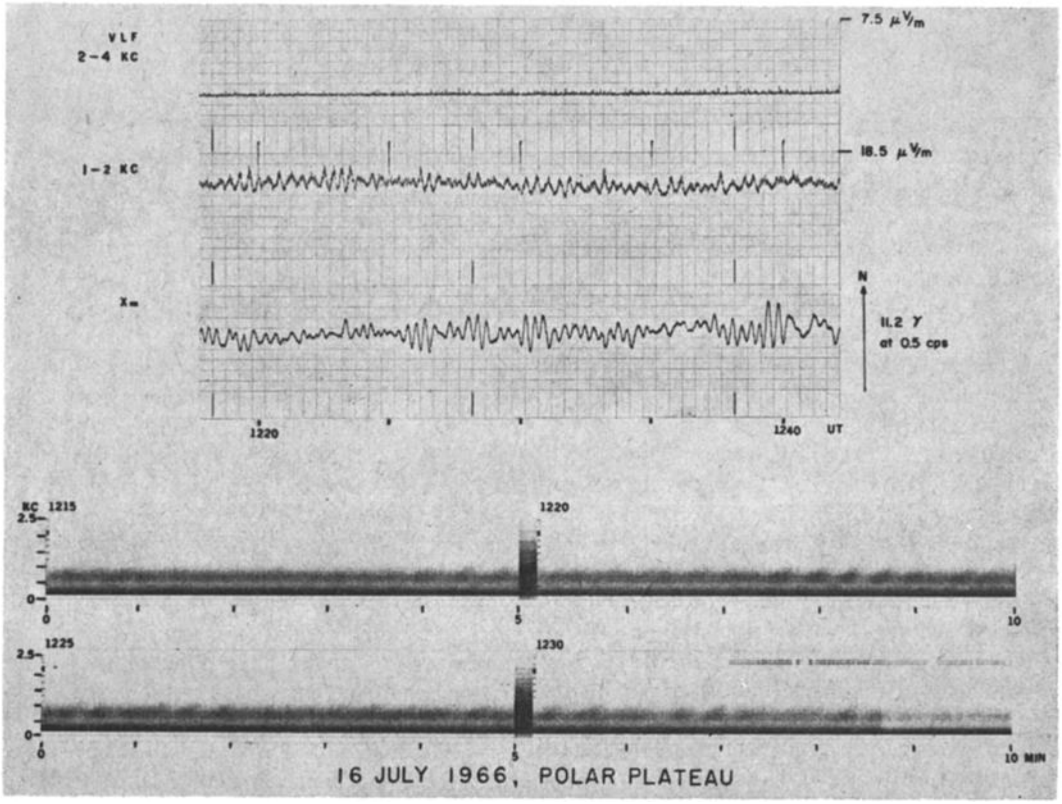

Fig. 5. An example of a GP-associated QP event.

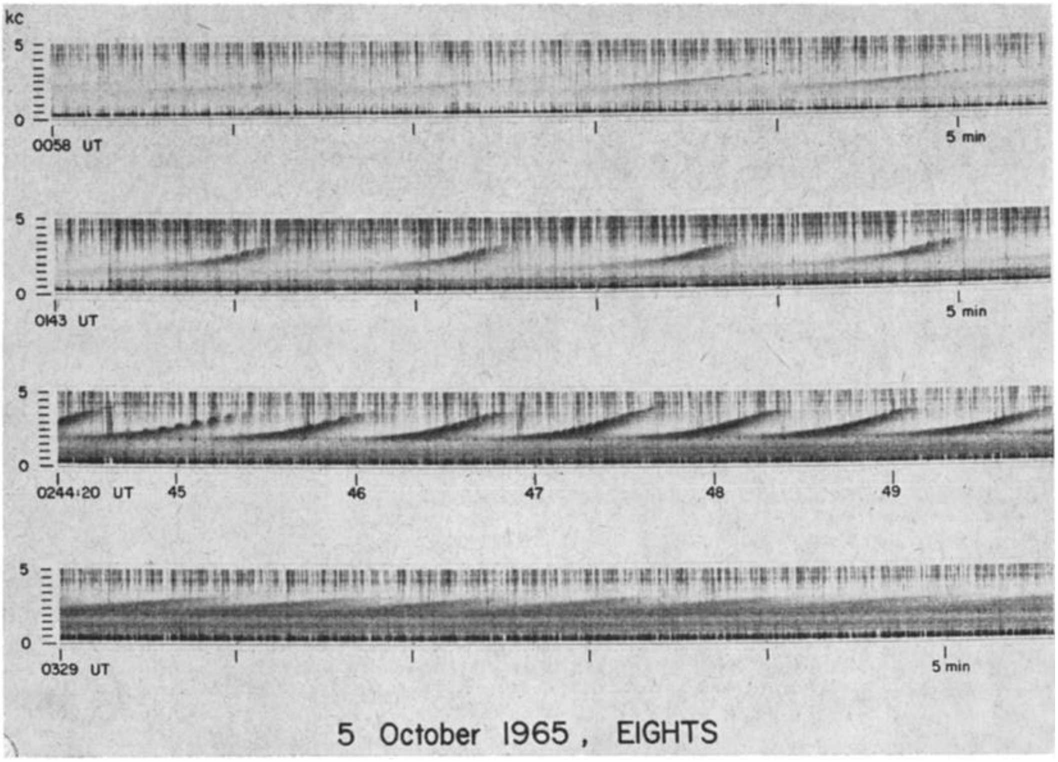

Fig. 6. An example of a QP event without any corresponding GP activity. The quasi-period becomes shorter and the rate of the frequency increase with time greater as the signal strength is enhanced. The emission is mostly diffuse.

we call low-frequency hiss. Three events (numbers 3, 4, and 22) consist purely of low-frequency hiss. Figure 5 shows event number 22. The sample of the chart record in the top half of the illustration shows the apparent similarity in period between the VLF emission and the magnetic field variations. The spectrum sample at the bottom shows that the QP emission is nondiscrete and has little frequency structure. (Whereas this emission would appear to lie below the range of the 1–2.4 kHz filter, the lower end of the frequency response of the filter falls off slowly enough to allow the QP to appear on the chart.) A discrete whistler-mode periodic is sometimes superimposed on low-frequency hiss with QP variations as in event number 5 (not illustrated). The spectra of two events (numbers 7 and 9) consist of the superposition of low-frequency hiss and chorus. Event number 7 is illustrated in Figure 3 and has already been briefly discussed. From a comparison of the spectrum samples at 1450 and 1550 UT in Figure 3 it is obvious that the basic spectral structure of the VLF emission did not change with the onset of the quasi-periodicity. The spectrogram obtained during the latter period shows that the upper boundary of the emission band varies during one QP period increasing as the signal strength becomes stronger. This characteristic frequently occurs in GP-associated QP's. In all these cases the QP variations appear primarily in hiss rather than in chorus or periodics.

QP's without Associated GP Activity

Figure 6 (event number 18) shows a typical example of QP's without any corresponding GP activity. Its spectrum again consists of diffuse emissions. As shown in the figure the center frequency of the emission increases without interruption during each quasi-period. Four other events, numbers 1, 2, 19, and 20, also exhibit the same behavior. A similar uninterrupted increase in frequency during one QP period is shown in event number 21 (Figure 7), where the emission is comparatively discrete, and in two events (numbers 12 and 14) in which the spectra consist of the superposition of diffuse noise and discrete emissions. In eight cases out of the total of ten events lacking in any corresponding GP activity, the center frequency of the emission increases without interruption during each quasi-period. Only two events, numbers 13 and 17, do not show this trend. The spectra of the VLF emissions in these two events are quite different from those in the eight cases mentioned above. Samples of the spectrograms of these two events are shown in Figure 8. The VLF activity in the first case is a rather unusual whistler-mode periodic emission that occurs in a narrow band at about 1 kHz. Part of the spectrogram of event number 17 is shown at the bottom of Figure 8. The VLF activity consists of closely spaced loud risers above a diffuse QP emission centered at about 3 kHz. These two events are widely different from each other and from the more common nonassociative QP's. They are shown to indicate the variety of forms that QP's may take.

The emission frequencies of QP's without any corresponding GP activity are generally higher (1.5–6 kHz) than those of GP-associated QP's as shown in Figure 9. As shown in Figure 6, the quasi-period of event number 18 becomes longer as the signal strength becomes weaker. This tendency is also seen in five other events, numbers 11, 13, 15, 19, and 20. In Figure 6, not only the quasi-period, but also the rate of increase of emission frequency is dependent on signal strength, being greater for stronger signals. This characteristic has also been found in a few other events.

QP's with Complicated Spectral Structures

For the five remaining QP's (numbers 6, 10, 11, 15, and 16), it is difficult to decide whether or not there is any associated GP activity. These events have more complicated spectra than those QP's for which GP activity is clearly associated or clearly not associated, and the spectral structures are quite different. Event number 10 is similar to that illustrated in Figure 8 in that many of the QP elements exhibit whistler-mode periodic internal structure, although at times the periodics merge to form a diffuse QP element. Event number 11 is also similar although much more diffuse. Both events appear to have rising QP elements. In event

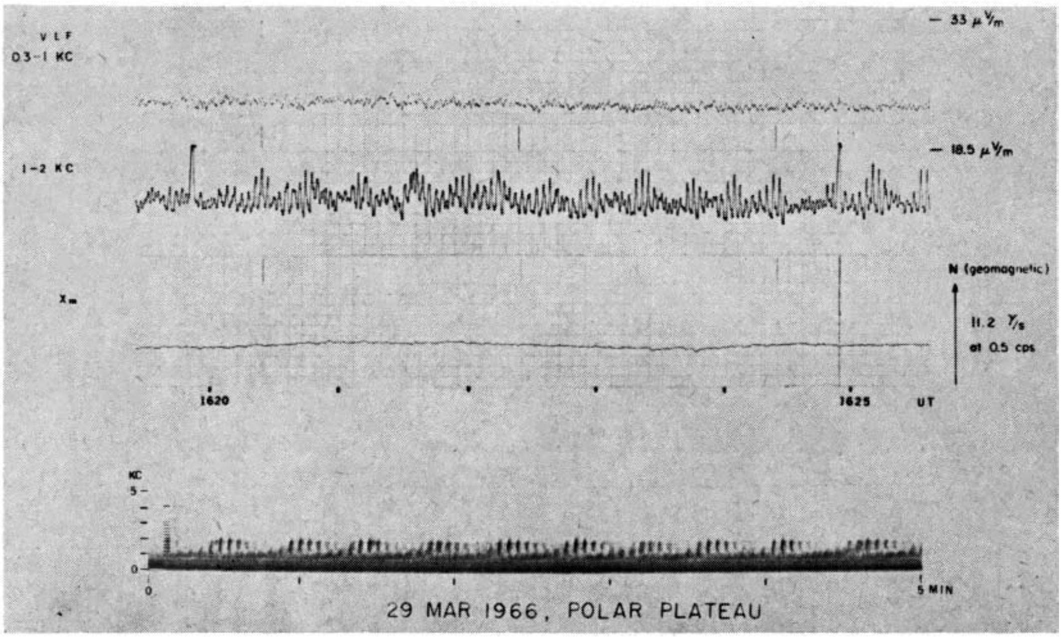

Fig. 7. An example of a QP event without any corresponding GP activity. The VLF emission is discrete.

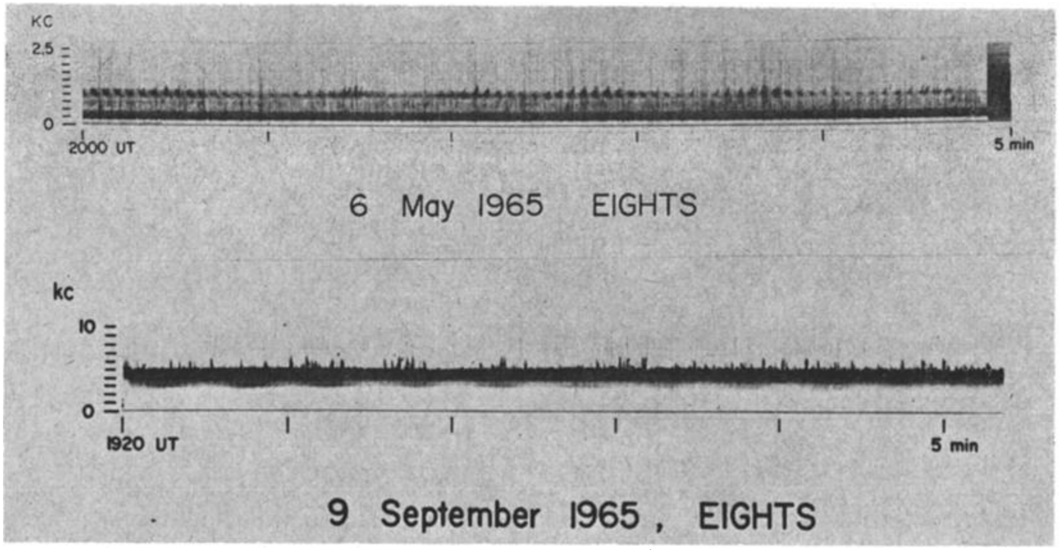

Fig. 8. Two examples of unusual QP events without corresponding GP activity. The first is a whistler-mode periodic confined to a narrow band near 1 kHz with QP variations in signal strength. The second is a band of noise between 4 and 5 kHz in which the noise at the lower end of the band varies with the QP period.

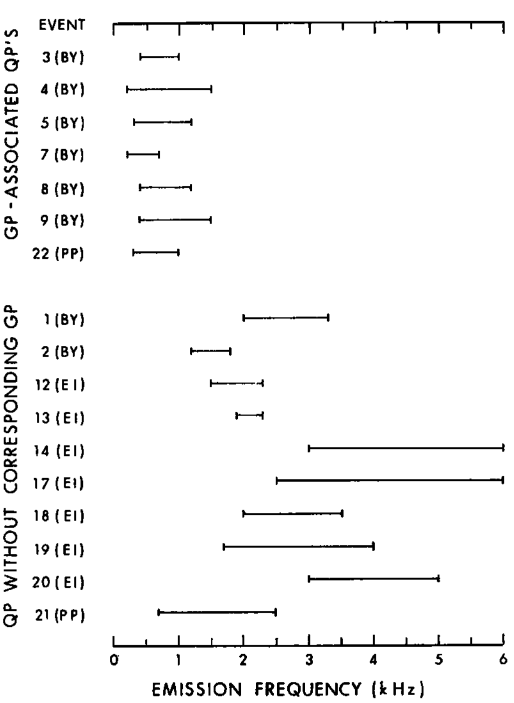

Fig. 9. The emission bandwidths of QP's. The emission frequencies of GP-associated QP's are generally lower than those of QP's without corresponding GP activity.

number 15 the QP takes place in a narrow band of nondiscrete noise centered at about 1 kHz. Although at the beginning of the event the QP appears to consist of only amplitude variations, it too develops a rising structure later. Event number 16 is made up of two simultaneous QP's. One is diffuse, and the other contains much discrete structure, but in both QP's the individual elements rise. The GP activity does not seem to be associated with either QP. In these four cases the spectral structure of the VLF activity lies somewhere between that of events in which QP's are apparently associated with GP events and that of events that clearly show no association.

Event number 6 (Figure 10) is a special and interesting case. It can be seen that the GP and QP have very nearly the same period. Furthermore, the amplitudes of the GP and QP variations decrease at nearly the same times at about 1716, 1724, and 1733 UT. By our definition of a GP-associated QP, this event is GP-associated. Peak-to-peak correspondence occurs only occasionally. A detailed study of the spectrogram reveals that the whistler-mode periodic emission of which the QP is made up consists of two parts with slightly different periods. One part is above 1.2 kHz and is nondispersive. The other part is below that frequency and shows dispersion. The lower periodic appears to trigger the upper one [*Helliwell*, 1965], which then runs independently until the two periodics approach 360° phase difference at which time the lower periodic triggers a new series of periodics in the upper frequency band and the old one dies out. The minima of the QP occur at the times of retriggering. This process suggests a QP mechanism independent of GP variations. However the over-all similarity of the QP and GP variations seems to indicate a still more complex interaction in which not only retriggering but also GP variations of the magnetic field contribute to the QP variations of the VLF activity. This event offers much potential for further investigation.

Magnetoconjugacy of QP's

Eight cases were found in which at one or both of the two magnetoconjugate stations, Great Whale River, and Byrd Station, a QP event was observed. In five of these cases GP activity was found to be conjugate and the QP was of the type associated with GP activity. (In this context, conjugacy of QP's or GP's is taken to mean that the forms of activity at two conjugate stations are recognizably similar). In four of the five cases (events number 3, 7, 8, 9) spectrograms of the VLF emissions from both stations have been examined. Despite the conjugacy of the GP activity, the QP was conjugate only in one case, event number 9 (Figure 11). GP activity is seen to begin at both stations at 2004 UT and to change to long-period pulsations at 2025. Conjugacy of the VLF activity may be seen in the QP ending at 2022. The QP takes place in a band about 0.4 kHz, and is most obvious in the Byrd Station sample at 2020. VLF activity develops into a normal periodic seen at both stations in the records at 2050. Event number 7 (Figure 2) is an example of a QP that lacks conjugacy. In this event and the other three cases for which

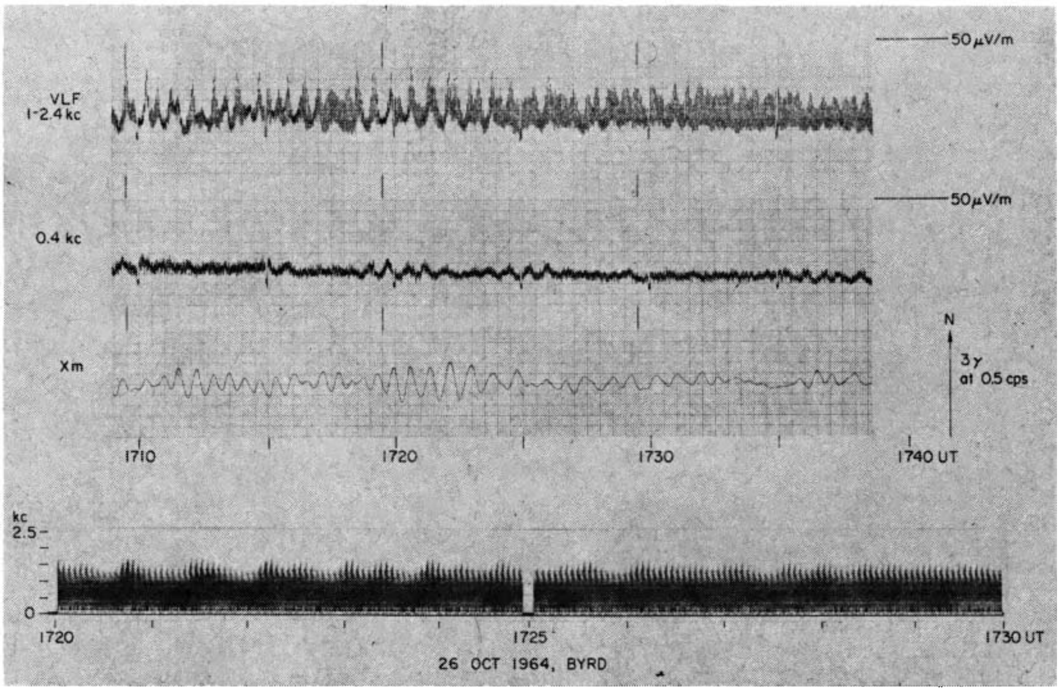

Fig. 10. A QP event with a complicated spectral structure. The VLF emission consists of two whistler-mode periodic emissions with slightly different periods and low-frequency hiss. The upper frequency boundary of the periodic emission as well as the signal strength of the low-frequency hiss appear to change with a period comparable with that of the simultaneous GP activity.

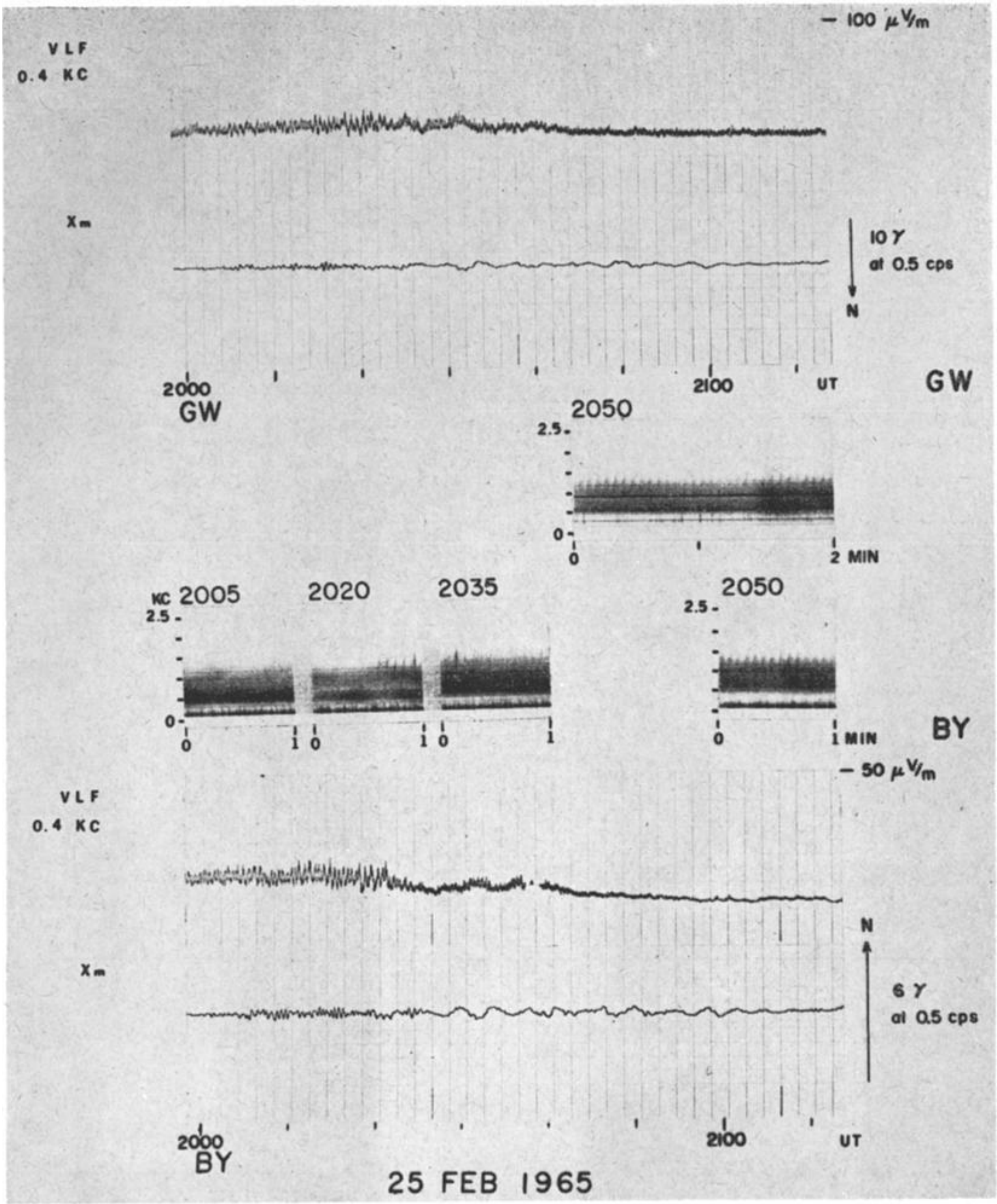

Fig. 11. A GP-associated QP event observed at conjugate stations. Basic forms of the VLF emission and GP activity are similar. The QP appears most clearly in the spectrum sample at 2020 UT at about 0.4 kHz.

TABLE 3. Magnetoconjugacy of Quasi-Periodic VLF Emissions

Conjugacy of GP Activity	Conjugacy of QP Activity	Number of Events
Yes	Yes	1
Yes	No	4
No	Yes	0
No	No	1
No GP activity at either station	Yes	2

no conjugate QP's were found, not only the QP but all VLF emissions lacked conjugacy. Differences in absorption may account for some of the lack of conjugacy, but the lack of conjugacy in four out of five cases suggests that the sources of the VLF noise may be local. In event number 9 the noise may be present at both ends of the path by coincidence and modulated by the conjugate GP event. The results of the investigations of conjugacy are summarized in Table 3.

We have not investigated the conjugacy of nonassociative QP's, but both *Carson et al.* [1965] and *Helliwell* [1965] show several examples of QP's with rising elements (and therefore our nonassociative type), which are not only conjugate but are received at widespread stations in one hemisphere.

Summary and Discussion

Table 4 summarizes the distinguishing characteristics of GP-associated QP's and QP's without corresponding GP activity. *Carson et al.* [1965] found that the long-period pulsations that they examined *always* rise in frequency during each element. Thus it appears that their investigation was limited to the type of QP, which is not associated with GP's. (They found only that QP periods fall into the general *range* of GP periods over the course of hours.) They identified QP's from a low time resolution spectrographic form of data from which the 'low frequency hiss' type of QP would be much more difficult to identify than from the chart amplitude records used in this paper.

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TABLE 4. Summary of Characteristics of GP-Associated QP's and Nonassociated QP's

	GP-Associated QP	QP without Corresponding GP
Emission spectrum	Low frequency hiss, often superimposed on chorus and/or periodic emissions.	Diffuse or discrete emissions or a combination of both.
Emission frequency range, kHz	0.3–1.5	1.5–6
Time change of emission frequency	Emission frequency may be constant or the upper boundary of the emission band may change in synchronism with the signal strength.	Increases during one quasi-period. Only two out of ten cases did not show this trend.
Magnetoconjugacy	Four cases out of five lack conjugacy.	Frequently conjugate, according to other references.
Change of quasi-period with VLF signal strength	No change noted.	Becomes longer as VLF signal becomes weaker.

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