Properties of structured and unstructured Pc1 pulsations at high latitudes: Variation over the 21st solar cycle

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Abstract

In this paper we study the properties of the two dominant types of Pc1 micropulsations observed at high latitudes, structured and unstructured pulsations, and present quantitative results on their behaviour over the 21st solar cycle. This analysis covers the two spring equinox months (March and April) in two sunspot minimum years, 1975-76, and in two maximum years, 1979-80. A strong depletion of both Pc1 types is observed in sunspot maximum years with the amount of structured pulsations being slightly more depleted than unstructured pulsations. We present the diurnal distributions of both pulsation types for minimum and maximum years separately and note on interesting changes over the solar cycle. We have also calculated the average period of the two pulsation types during the two sunspot phases. While the average period of unstructured Pc1's remains nearly constant, the average period of structured pulsations is found to increase in sunspot maximum years. This high-latitude result is opposite to observations at low and mid-latitudes. Finally, we discuss the observed solar cycle changes in terms of the deterioration of the ionospheric wave guide in sunspot maximum years and the development of the plasmapause.

Introduction

The solar cycle variation of the occurrence of Pc1 micropulsations has been studied both at low and mid-latitudes [Benioff, 1960; Fraser-Smith, 1970 and 1981; Matveyeva et al., 1972; Strestik, 1981; Fujita and Owada, 1986; Matveyeva, 1987] and at high latitudes [Kawamura et al., 1983; Mursula et al., 1991]. The main result from these studies, roughly valid for all latitudes, is that the dominant feature in the long-term behaviour of the Pc1 activity is the sunspot cycle, and that more Pc1 pulsations occur during the sunspot minimum years than during the maximum years. Even in a more detailed comparison [Mursula et al., 1991], the long-term Pc1 activity curves at low and high latitudes were shown to have interesting similarities, following the changes in the annual sunspot activity from one solar cycle to another.

Some differences are also known to exist in the long-term Pc1 cycles at different latitudes. The inverse relation between sunspot numbers and Pc1 occurrence at low and mid-latitudes is only approximate. Fraser-Smith [1970] and Matveyeva et al. [1972] have reported that the low- and mid-latitude Pc1 events have their maximum occurrence rate during the declining phase of the sunspot cycle rather than at the minimum. This behaviour differs from the strong and direct negative correlation observed between annual sunspot numbers and the low-frequency Pc1's at high latitudes [Mursula et al., 1991] with a Pc1 maximum at sunspot minimum times. However, these seemingly contradictory observations may be reconciled when the different frequency ranges and the differences between the structured and unstructured pulsations, the two dominant pulsations types at high latitudes, are taken into account.

While structured pulsations (also called periodic or pearl emissions) are the dominant Pc1 pulsation type at low- and mid-latitude stations [Fraser-Smith, 1970; Kawamura, 1970; Kuwashima et al., 1981], the majority of Pc1 pulsations at high latitudes are unstructured pulsations, particularly of the type of hydromagnetic chorus [Nagata et al., 1980; Fukunishi et al., 1981]. Many properties, e.g. diurnal distributions and average frequencies, are known to be different for structured and unstructured pulsations [Kuwashima et al., 1981]. It has also been found that structured pulsations are intimately related to the evolution of magnetic storms [Wentworth, 1964; Plyasova-Bakunina and Matveyeva, 1968; Kuwashima et al., 1981], but the unstructured pulsations do not show such a dependence [Kuwashima et al., 1981]. These dramatic differences have led to the present view that, while the source region of structured pulsations is close to the plasmapause, the unstructured pulsations originate at much higher latitudes.

In the present paper we study the properties of structured and unstructured Pc1 pulsations observed at high latitudes, concentrating on the variation of these properties over the minimum and maximum phase of the 21st sunspot cycle. In the next section we will introduce the equipment used and the data collected for this analysis. Then, in section 3 we will present our results for the occurrence rates of structured and unstructured Pc1's. Section 4 deals with the diurnal distributions and their changes over the solar cycle. The results for the Pc1 period are presented in section 5. In section 6 we will discuss our observations on solar cycle changes of Pc1 properties trying to reconcile the seemingly disagreeing results on the sunspot cycle changes of Pc1 pulsations at different latitudes. Section 7 concludes the paper.

Equipment and data

In this study we used data from a search-coil magnetometer situated at the high-latitude station of the Sodankyl Geophysical Observatory (geographic coordinates 67.4° Lat, 26.6° Long, corrected geomagnetic coordinates 63.9° Lat, 109° Long, L=5.2), Finland. The output signal from the magnetometer is amplitude modulated and registrated in analogue form on 6"/h and 24"/h magnetic tapes. The magnetic registrations were analyzed with an analogue/digital sonagraph (Model 5500, Kay Elemetrics Corp.), and sonagrams were made for any Pc1 range activity detected.

The main aim of the present study is to examine the variation of the properties of Pc1 pulsations during two opposite phases of the solar cycle. For that purpose, we decided to compare the two equinox months, March and April, of the two sunspot number minimum years 1975-76 with the same months of the two maximum years 1979-80 of the 21st solar cycle. Restricting the analysis to just a couple of months per year made it possible, firstly, to decrease the amount of events to be analyzed and, secondly and more importantly, to minimize the influence of seasonal variations which might mask out the solar cycle variations. (It is known since long ago [Benioff, 1960; Strestik, 1981] that e.g. the diurnal distribution and some other properties of structured Pc1's show seasonal variations). Using data from two years for both phases of the sunspot cycle, we could increase statistics and decrease random fluctuations in data. This also helps in balancing the fluctuations in magnetic activity and in the occurrence of magnetic storms that are an essential factor especially for structured pulsations. By the choice of equinox months we could maximize the number of structured Pc1 events whose annual occurrence maximizes at equinoxes [Fraser-Smith, 1970].

The observed Pc1 pulsation events were divided into five types according to the morphology of the sonagram (dynamic spectrum) of the event. The first type consists of classical structured Pc1's which show clear repetitive intensity maxima. Unstructured pulsations, which do not show such regular intensity variation, form the second Pc1 type. They mainly consist of hydromagnetic chorus and Pc1-2 band-type events according to the classification of Fukunishi et al. [1981]. In Figure 1 sample sonagrams of these two types are presented. Structured and unstructured Pc1's form the large majority of all events observed at Sodankyl (see section 3) and the remaining three groups are just a rather small fraction of all Pc1 events observed. In the present analysis we will neglect these three small Pc1 groups and concentrate on the two dominant Pc1 types, the structured and unstructured pulsations.

The properties of the detected Pc1 events were registered for each hour. We noted the start time and duration of each clearly separate Pc1 band, as well as its type, its maximum intensity during the hour and its possible continuation from the previous hours. Furthermore, for each hour and event, we noted the highest and lowest frequency and the mid-frequency at the hourly intensity maximum. In case of occasional multi-band Pc1 events, we treated each band as a separate event with its own properties. When studying the frequency of magnetic pulsations one should actually correct the raw data of each event with the frequency response of the magnetometer. However, because the Pc1 pulsation bands have quite a narrow frequency range of about 0.1-0.2 Hz, the average frequency of a Pc1 band, which is the main frequency property to be studied, remains practically constant in this correction. Therefore we can neglect the enormous amount of work needed for a complete correction of all Pc1 events, and use the raw data in our frequency analysis.

Pc1 occurrence in minimum and maximum years

We observed altogether 677 Pc1 events during the 8 months analyzed, with a total Pc1 active time of more than 42 days. The average length of all Pc1 events was about 90 minutes. The number of events and the total Pc1 active time in minutes are given in Table 1 separately for structured, unstructured and other pulsation types and the two intervals with minimum and maximum sunspot activity. We have also calculated the relative percentage of the two pulsation types during each interval.

First of all, one can see from Table 1 that there is a strong reduction in the overall Pc1 activity from the low sunspot years 1975-76 to high activity years 1979-80. While Pc1's appear up to about 30% of the time during minimum years, total Pc1 activity during maximum years is almost one order of magnitude lower. This is in accordance with the previous results showing a strong negative correlation between Pc1 activity at high latitudes and sunspot activity (see e.g. Mursula et al., 1991, and references therein). We would also like to note here that the Pc1 events during maximum years were found to be less intensive on an average than during minimum years.

Secondly, we can now also verify that the reduction in the occurrence of Pc1 pulsations during high sunspot number years is separately true for the two dominant Pc1 types at high latitudes, i.e. the structured and unstructured pulsations, as well as for the remaining Pc1 pulsation types in total. However, the amounts by which the different pulsation types have been reduced seem to be different. While the structured Pc1's were reduced nearly by one order of magnitude over the sunspot cycle, the corresponding factor for unstructured pulsations was about 7. The remaining Pc1 types were reduced even less, i.e. by factor 3.

It is interesting to note that the relative fraction of unstructured pulsations remained constant over the sunspot cycle so that 53% of all Pc1 activity both in minimum and maximum years were classified as such. On the other hand, due to the above mentioned large reduction factor, the relative fraction of structured pulsations in maximum years (30%) was smaller than in minimum years (40%). This reduction is seen as an increase in the relative amount of other types of Pc1's during maximum years. A possible explanation could be that those effects that cause the general reduction in Pc1 activity in maximum years may more strongly affect structured pulsations that are vulnerable to lose the coherence of the wave packets and thus to get misidentified.

Furthermore, using the values given in Table 1 for the Pc1 active time and the number of events, one can get an estimate for the average duration of Pc1 events of each type. In sunspot minimum years, the average durations of structured and unstructured Pc1 pulsations are approximately the same (about one hundred minutes) but the other events are shorter by roughly a factor of two. In sunspot maximum years, the average duration of structured pulsations remains approximately the same as in minimum years but the unstructured pulsations get shorter by a factor of 2, being thus approximately as short as the remaining Pc1 events whose average duration remains the same over the sunspot cycle.

Diurnal distributions in minimum and maximum years

We have calculated the diurnal variation of the structured and unstructured Pc1's by counting the hourly duration of events of these two types separately. The results for the minimum and maximum sunspot years are presented in Figures 2 and 3, respectively. As can be seen in Figure 2, the distribution for the unstructured pulsations in minimum years attained an almost Gaussian form around the maximum at 11 UT (local time is 2 hours ahead of UT, MLT about 3 hours). Its nighttime activity was more than an order of magnitude lower than in daytime. On the other hand, the diurnal distribution of structured Pc1's in minimum years had a far less pronounced maximum in late morning hours. Its activity remained relatively high throughout the day and night, exceeding that of unstructured pulsations outside the noon-afternoon sector.

In sunspot maximum years (see Figure 3), the pronounced postnoon maximum of the unstructured pulsations also exists but seems to be shifted by 1-2 hours later. Unstructured Pc1 activity outside this postnoon maximum was relatively larger in maximum years, in particular in the early morning sector where a secondary maximum appeared. Note that the overall activity around this secondary maximum was only reduced by a factor of 2 from minimum years, while around the postnoon maximum this reduction was considerably larger.

The diurnal distribution of structured Pc1's in maximum years was also slightly different from that in minimum years. Structured Pc1's almost exclusively appeared during morning hours. It is curious to note that the time of appearance of structured Pc1's fits very nicely with the minimum between the two maxima in the distribution of the unstructured pulsations.

Average Pc1 period in minimum and maximum years

In order to study the solar cycle behaviour of the period of Pc1 pulsations we have calculated the average of the observed mid-frequency at the hourly intensity maximum for structured, unstructured and the remaining Pc1's and the two sunspot phases separately. These results are also presented in Table 1. In addition, we have repeated this procedure for the average value of the highest and lowest hourly frequencies. In Table 1 we call this the "band average". As can be seen in Table 1, the values derived for the average frequencies using the two methods are very close to each other, giving additional confidence in the results obtained.

Table 1 shows that there are notable differences in the average frequencies of the different pulsation types. For example, the results verify in a quantitative way the earlier qualitative observation [Fukunishi, 1981] that the average frequency of structured pulsations is higher than that of unstructured pulsations. In sunspot minimum years (1975-76) this difference was as large as 0.32-0.33 Hz. The average frequency of the remaining events in minimum years was nearly the same as that of structured Pc1's.

In sunspot maximum years (1979-80) the average frequencies of all pulsation were at least a little lower than the corresponding values in minimum years. This decrease was particularly large for structured pulsations while unstructured pulsations remained nearly at the same value and other pulsations experienced a smaller decrease. Accordingly, the difference between the average frequencies of structured and unstructured pulsations in maximum years was slightly smaller (about 0.24-0.25 Hz) than in minimum years.

The general tendency of decreasing Pc1 frequencies could, at least in principle, also result from an instrumental (rather than a physical) effect, e.g. due to the roaming of the frequency response of the magnetometer. However, such roaming has not been observed in the annual calibrations. Furthermore, the observed changes do not support such an interpretation. In minimum years, structured and group three (other) pulsations had identical average frequencies while in maximum years they had different average frequencies. If the frequency shift were purely an instrumental effect, the average frequencies of these two groups should change by equal amounts.

Discussion

As already mentioned above, our observations verify the strong depletion of all main types of Pc1 micropulsations at high latitudes during sunspot maximum years. This is particularly interesting from the point of view of our previous analysis [Mursula et al., 1991] where a strong negative correlation between the annual low-frequency Pc1 activity and annual sunspot number was found at high latitudes over several solar cycles. However, it was not possible to make a distinction between the different pulsation types in that analysis.

The observed decrease of the average frequency of all pulsation types from 0.58-0.60 Hz in minimum years to 0.51-0.52 Hz in maximum years is also relevant for the interpretation of our earlier results [Mursula et al., 1991]. In that analysis only pulsations at the eigenfrequencies of 0.3 Hz and 0.5 Hz were detected. Thus the observed negative correlation could be explained by a possible rise of the average Pc1 frequency with increasing sunspot number, and not due to the actual depletion of Pc1 activity. Therefore the present observation of a decreasing (and not increasing) average Pc1 frequency with increasing solar activity excludes this interpretation and gives further confidence in the method used and the results obtained in that analysis.

The observed diurnal distribution of unstructured pulsations agrees well with the post-noon maximum of magnetospheric ion cyclotron waves recently detected by Anderson et al. (1992) in a large statistical analysis using the AMPTE/CCE satellite. They also observed that the probability to find these waves increases with latitude and is much higher at auroral latitudes (L$\simeq$ 7-8) than at mid-latitudes (L$\simeq$ 3-4). This also agrees with the observed increase of total ground-based Pc1 activity with latitude [Troitskaya and Gul'elmi, 1970]. Since unstructured pulsations are detected almost exclusively at high latitudes it is very likely that the waves detected by Anderson et al. (1992) are the source of unstructured pulsations.

It has been known since long that the daily distribution of structured pulsations at low and mid-latitudes has its maximum at dawn (for a review see Saito, 1969). This has been connected with the minimum in the ionospheric ionization resulting in better propagation conditions of the ionospheric wave guide in early morning hours. However, our observation for the diurnal distribution of structured Pc1's shows that, at high latitudes, this maximum occurs later than at low or mid-latitudes and also later than the local minimum in the ionospheric ionization. This difference may be due to the fact that the high-latitude source can also produce structured pulsations to be detected on ground at high latitudes. Thus the high-latitude station of Sodankyl receives part of the structured pulsations from plasmapause which normally is located at lower latitudes, and part from the higher latitude source. This view is further supported by the fact that the average frequency decreases from morning till noon when approaching the high-latitude source. On the other hand, the mid- and low-latitude stations would, due to the longer ducting distance, only observe the lower latitude plasmapause connected events.

The differences in the diurnal distributions between sunspot maximum and minimum times may be explained by the fact that the ionospheric ducting conditions are worse in maximum years, especially at the dayside. This may be the reason e.g. to the greater depletion of unstructured pulsations around the local noon than in the early morning sector, leading to the formation of the secondary maximum in early morning hours and shifting the diurnal maximum of unstructured pulsations by 1-2 hours later. Note that the time of the secondary maximum corresponds well with the time of minimum ionospheric ionization. The fact that structured pulsations are more depleted in maximum years outside morning hours may also reflect deteriorated ducting conditions.

The observed decrease of the average frequency of high-latitude structured pulsations with solar activity is very interesting in view of the fact that, correspondingly, an increase (rather than decrease) was observed in maximum and post-maximum sunspot years at low and mid-latitudes [Strestik, 1981; Matveyeva, 1987]. Supposing that the ionospheric wave guide is deteriorated during sunspot maximum years, the stations would mainly observe pulsations whose footpoint is quite close to the station. Accordingly, in maximum years, the low- and mid-latitude stations would observe those events for which the plasmapause is located at lower latitudes than on an average while in minimum years they would register events also from further off. Since the average pulsation frequency decreases with increasing latitude for L-values up to about L$\simeq$ 5-7 [Erlandson et al. 1990; Anderson et al., 1992], this implies that the average frequency at low and mid-latitudes is higher in maximum than in minimum years.

On the other hand, the same mechanism implies that a high-latitude observer that is located outside the average plasmapause would, in maximum years, only detect those plasmapause connected structured events where the plasmapause is at higher latitudes than on an average. This observer would, opposite to the low-latitude observer, find that the average frequency decreases (rather than increases) in maximum years. However, due to the high-latitude source, the situation is more complicated at high latitudes than low latitudes.

There is another mechanism contributing to the difference between the average frequencies at low and high latitudes. This mechanism is related to the change of the average plasmapause location over the solar cycle. Following the more frequent occurrence of storms, the plasmapause is, on an average, at lower latitudes in maximum years. This implies that the average frequency of structured pulsation rises in maximum years, in accordance with what is observed at low and mid-latitudes. (Note that this mechanism incorrectly predicts that more events are observed in maximum years than minimum years. Therefore this mechanism alone can not be responsible for all observations). Accordingly, the two mechanisms (ducting conditions and plasmapause location) work in the same direction as to the change of the average frequency at low and mid-latitudes.

At high latitudes, the two mechanisms work oppositely: deteriorated ducting conditions decreasing the average frequency of structured pulsations, and lower plasmapause location increasing it. The lower position of the plasmapause would also imply less of plasmapause related events at high latitudes due to longer propagation distance. Thus the relative significance of the high-latitude source with low frequency would increase leading to a lower average frequency of structured pulsations at high latitudes. The plasmapause mechanism can also explain the observation that structured pulsations are relatively more depleted at high latitudes than unstructured or other Pc1 types. (Note that this mechanism predicts correctly a depletion of structured pulsations in maximum years at high latitudes. Again, however, it is not sufficient alone since it does not explain the depletion of unstructured Pc1's).

The average frequency of unstructured pulsations was observed to remain nearly constant over the solar cycle. Since their source is at high latitudes and the average frequency of this high-latitude source remains constant with latitude beyond L$\simeq$ 5-7 [Erlandson et al., 1990; Anderson et al., 1992], our observation of the constancy of the frequency of unstructured pulsations is in accordance with the above idea of deteriorating wave guide. The observed decrease of the average duration of unstructured pulsations during sunspot maximum years may result from the deteriorated ducting conditions as well, reflecting natural intensity variations that may have remained unobserved during minimum years with stronger average pulsation intensity.

Finally, we would like to note that the time interval of two months is not very long in view of storm development. Accordingly, the results on structured pulsations that depend partly on the plasmapause development may be affected by the number and nature of storms occurring during the studied interval, and need to be verified using observations from longer time intervals or other solar cycles. Such an extended analysis is underway.

Conclusions

We have studied in this paper the properties of structured and unstructured pulsations, the two dominant Pc1 types at high latitudes, and presented new quantitative results on their behaviour over the 21st solar cycle. Strong depletion of both types of Pc1's was observed in maximum sunspot years. The main features of diurnal distributions with late morning and afternoon maxima for structured and unstructured pulsations respectively remained valid over the solar cycle. However, interesting differences between maximum and miminum years appeared in the detailed properties of these distributions. Furthermore, while the average frequency of unstructured pulsations remained nearly constant over the solar cycle, the average frequency of structured pulsations decreased slightly in maximum years, in contrast to the increase observed at low latitudes.

We discussed how these observations can be understood in terms of the deterioration of the ionospheric wave guide in sunspot maximum years. However, other effects have to taken into account as well, in particular the development of the plasmapause because of its connection with structured Pc1 pulsations.

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Figure Captions

Figure 1. Dynamic spectra for typical structured (top) and unstructured (bottom) Pc1 pulsations registered at Sodankyl on March 27, 1975, and March 6, 1976, respectively. The dark vertical lines are hour signals.

Figure 2. The diurnal distribution of the hourly duration of structured (open circles) and unstructured pulsation events (black circles) in minimum years.

Figure 3. The diurnal distribution of the hourly duration of structured (open circles) and unstructured pulsation events (black circles) in maximum years.

Table 1. Number of events, total times (minutes/ relative percentages) and average frequencies (Hz) of structured, unstructured and other Pc1 pulsations during sunspot minimum years (1975-76) and maximum years (1979-80).

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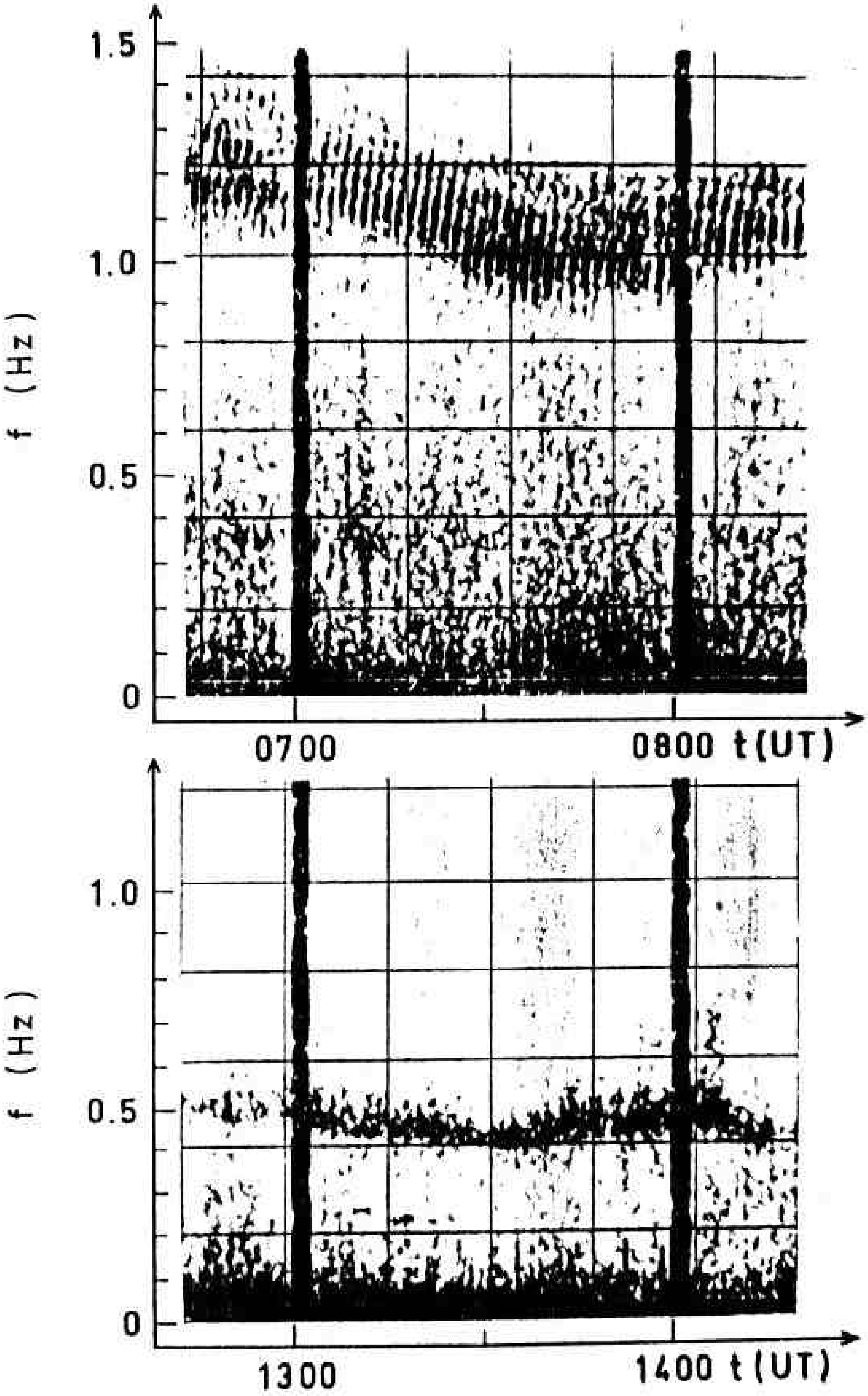

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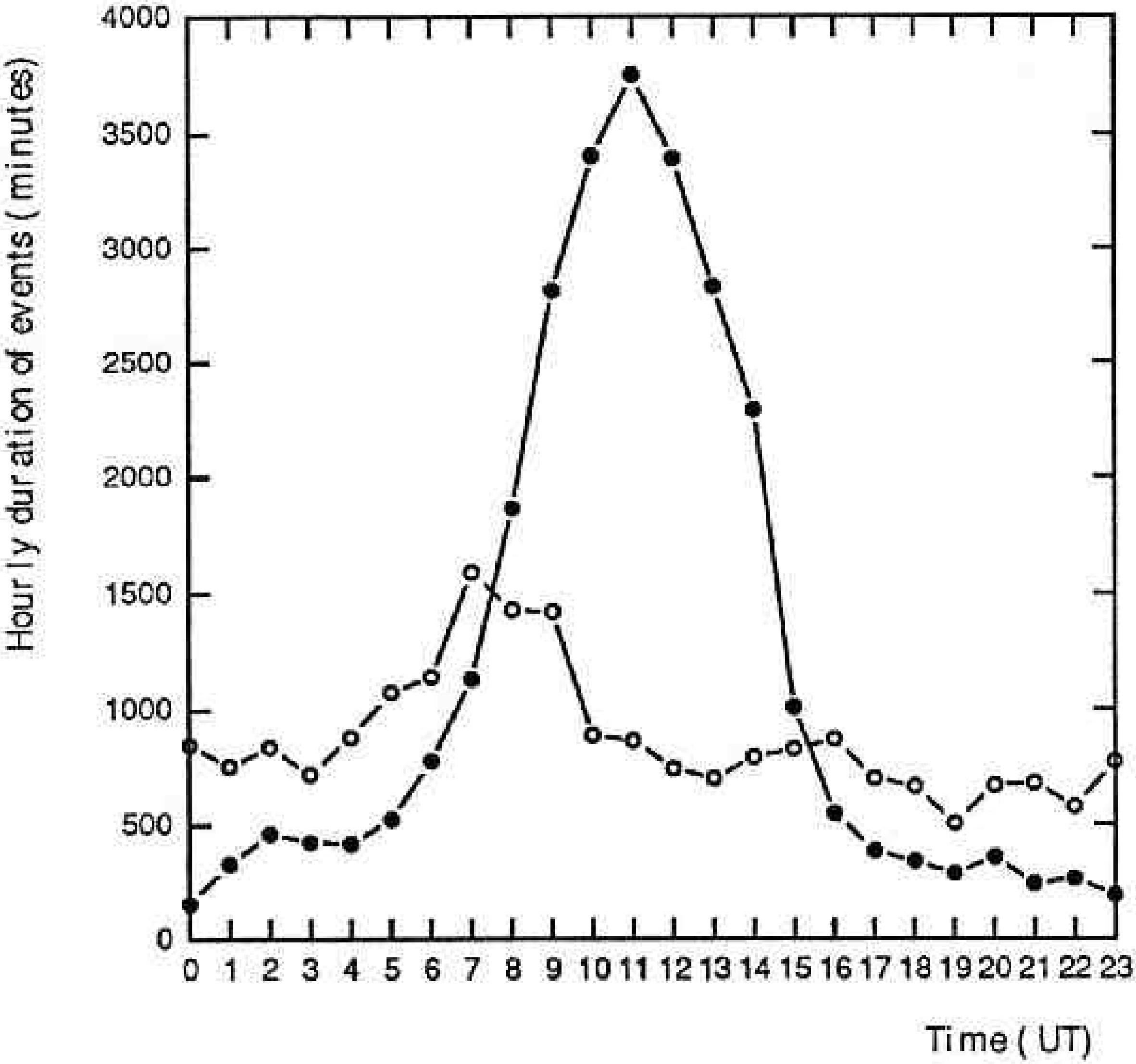

Figure 2. The diurnal distribution of the hourly duration of structured (open circles) and unstructured pulsation events (black circles) in minimum years.

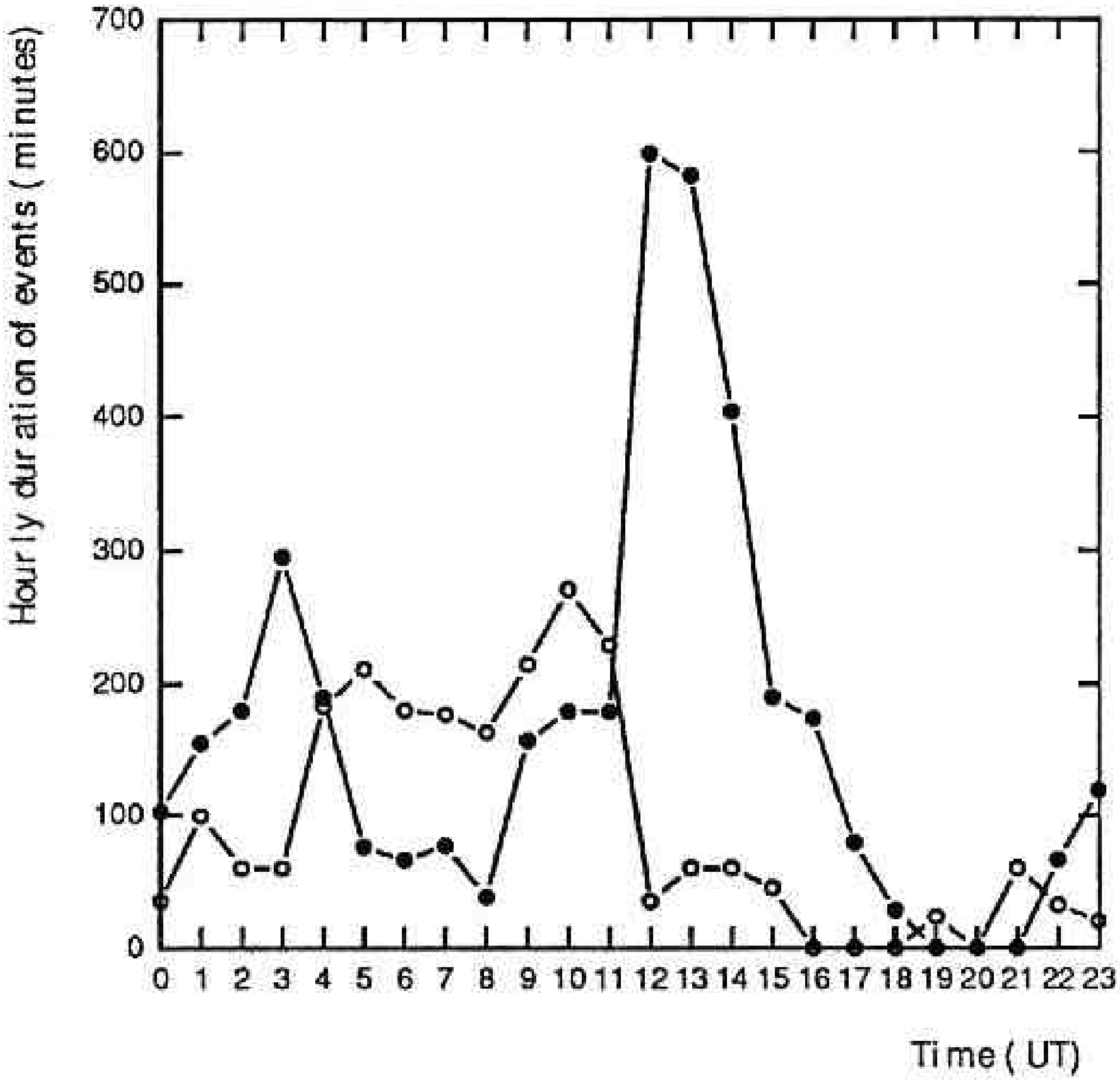

Figure 3. The diurnal distribution of the hourly duration of structured (open circles) and unstructured pulsation events (black circles) in maximum years.

	Number of events	Total time (min/%)	Average frequency (Hz) according to max. int.	band average
1975-76				
Structured	214	20975/40	0.75	0.77
Unstructured	266	28187/53	0.43	0.44
Other	72	3928/7	0.75	0.78
All	552	53090	0.58	0.60
1979-80				
Structured	21	2219/30	0.63	0.64
Unstructured	79	3936/53	0.38	0.40
Other	25	1292/17	0.70	0.69
All	125	7447	0.51	0.52

Table 1. Number of events, total times (minutes/relative percentages) and average frequencies (Hz) of structured, unstructured and other Pc1 pulsations during sunspot minimum years (1975-76) and maximum years (1979-80).