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Pc 1 Micropulsations at a High-Latitude Station: A Study Over Nearly Four Solar Cycles

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An old but rarely used resonance method is introduced and examined in order to study the very long term occurrence of Pc 1 micropulsations. By this method it is possible to detect Pc 1 pulsations with a frequency close to the eigenfrequency of the magnetometer system. We have analyzed the magnetograms of the LaCour-type magnetometer used in a quick-run operation at the high-latitude station of Sodankylä, Finland. The eigenfrequencies of the three components covered the frequency range from about 0.3 to 0.5 Hz. Our analysis extends over the whole registration period from 1932 to 1944 and from 1953 to 1983, i.e., covering nearly four solar cycles. The results show a very strong negative correlation between the annual Pc 1 activity and the annual sunspot number which persists over the whole data period. According to the statistics obtained, it is, for example, very unlikely that the Pc 1 activity maximum at a high-latitude station would occur during the declining phase of the sunspot cycle. Furthermore, as a result of the negative correlation, some of the differences between the various solar cycles can be seen in the corresponding cycles of annual Pc 1 activity. Our results also reveal some new features common for the long-term variations of Pc 1 activity at high- and mid-latitude stations and help in understanding the differences between them.

1. Introduction

Long-term variation of the occurrence of short-period micropulsations of the Pc 1 type has been studied by several authors [*Benioff*, 1960; *Fraser-Smith*, 1970, 1981; *Matveyeva et al.*, 1972; *Strestik*, 1981; *Kawamura et al.*, 1983; *Fujita and Owada*, 1986; *Matveyeva*, 1987]. While the longest series of observations, covering more than two solar cycles, have come until now from low- and mid-latitude stations, the only long-term study of Pc 1 occurrence so far made at a high-latitude station extends hardly over half a solar cycle [*Kawamura et al.*, 1983].

The general conclusion from the results of low- and mid-latitude stations is that the dominant feature in the long-term behavior of the Pc 1 activity is the 11-year solar activity cycle and that more Pc 1 micropulsations occur during the sunspot (SS) minimum years than during the maximum years [*Benioff*, 1960; *Fraser-Smith*, 1970, 1981; *Matveyeva et al.*, 1972; *Kawamura et al.*, 1983; *Fujita and Owada*, 1986; *Matveyeva*, 1987]. However, as we will discuss later in more detail, the results from the various low- and mid-latitude stations show some mutual differences [*Fraser-Smith*, 1970; *Matveyeva et al.*, 1972] and interesting deviations [*Matveyeva*, 1987] from this general pattern which are still not well understood.

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The same general conclusion, i.e., a negative correlation between the long-term Pc 1 activity and the sunspot cycle, was obtained by *Kawamura et al.* [1983] using the observations made at the auroral station of Syowa ($L=6.0$) during the first half of the 21st solar cycle from 1976 to 1980. It is by now well known that, while periodic emissions are the dominant Pc 1 pulsation type at mid- and low-latitude stations [*Fraser-Smith*, 1970; *Kawamura*, 1970; *Kuwashima et al.*, 1981], more than half of the Pc 1 pulsations at high latitudes are formed by the hydromagnetic chorus [*Nagata et al.*, 1980; *Fukunishi et al.*, 1981]. Periodic emissions and hydromagnetic chorus show widely different diurnal distributions and have different average frequencies [*Kuwashima et al.*, 1981]. It has also been found that the periodic emissions are intimately related to the evolution of magnetic storms [*Wentworth*, 1964; *Plyasova-Bakunina and Matveyeva*, 1968; *Kuwashima et al.*, 1981] and that the hydromagnetic chorus does not show such a dependence [*Kuwashima et al.*, 1981].

In view of these notable differences in the properties of the dominant forms of Pc 1 pulsations at high versus low latitudes, it is a remarkable and highly nontrivial fact that the long-term Pc 1 variations at both high-, mid-, and low-latitude stations have a roughly similar general behavior. Therefore it is necessary to study this approximate similarity in more detail and, particularly, to verify, over a much longer observation time, the result found by *Kawamura et al.* [1983] for a high-latitude station.

In this study we present the results of a very long term analysis of Pc 1 pulsations observed at the high-latitude station of the Sodankylä Geophysical Observatory (geographic coordinates 67.4° lat., 26.6° long., corrected geomagnetic coordinates 63.9° lat., 109° long., L=5.2), covering nearly four complete 11-year solar cycles, i.e., cycles 17, 19, 20, and most of cycle 21. While recordings of Pc 1 micropulsations by specific pulsation magnetometers (see, for example, *Campbell* [1967] or *Forbes* [1987]) have been available only since the late 1950s, the method to be presented and examined in this paper allows the possibility to extend the observations to as early as 1930s. Using this method, we can study the long-term variation of Pc 1 micropulsations at a high-latitude station in much more detail and during a much longer time period than up to now.

In the next section we will introduce the method and equipment used in this analysis. Then we will study the data set obtained and, in the fourth section, present the results of the comparison with the pulsation magnetometer data. In section 5 our main result on the long-term Pc 1 occurrence is given. In section 6 we compare the results from the various mid-latitude stations with each other and with the present observations. Section 7 concludes the paper.

2. METHOD AND EQUIPMENT

This analysis is based on the data obtained from the magnetograms of a LaCour-type magnetometer system (see, for example, *Chapman and Bartels* [1962] or *Forbes* [1987]) used in a quick-run (QR) operation mode at the high-latitude station of the Sodankylä Geophysical Observatory. Quick-run registrations were made at Sodankylä during two long periods, using two similar but not exactly identical magnetometers during the respective periods. The first period (to be called period I hereafter) extended from 1932 to 1944 and the second (period II) from 1953 to 1983. We have analyzed all the magnetograms recorded during these two periods.

Such a quick-run magnetometer system can detect and register short-period micropulsations in the frequency range close to the eigen-frequency of the magnetometer. The observed signal of short-period micropulsations is a characteristic and easily distinguishable widening of the magnetogram curve, resembling the form of a "bubble," or rather a chain of bubbles since they most often occur in groups of many bubbles, interrupted by short intervals (see Figure 1*a*). Actually, what is observed is the envelope of the oscillations. The individual oscillations, however, are not resolved by the system because of the slow motion of the registration system. It is also to be noted that bubblelike signals can be caused not only by periodic pulsations (for example, periodic Pc 1 emissions) but also by constant pulsations (for example, hydromagnetic Pc 1 chorus). In the latter case the bubblelike form of the signal is generated as a sum of the driving constant pulsation including a range of frequencies and the damping properties of the magnetometer.

Analogous signals were first observed and analyzed by *Harang* [1936] and *Sucksdorff* [1936]. Sucksdorff was also the first who correctly anticipated the connection of the signal with a new physical phenomenon, the short-period (or "rapid," as he called it) micropulsations. He also used the nickname "pearl necklace." However, as we already mentioned in the introduction, most Pc 1 pulsations at high latitudes are of the hydromagnetic chorus type, and therefore we prefer not to call these signals "pearls" because of the close connection of this name with the periodic emission type of Pc 1 pulsations.

The QR method of studying short-period micropulsations has many noteworthy assets. First, as we already mentioned, relevant data exist from much earlier years than available from, for example, specific micropulsation magnetometer systems. Second, using this method, the Pc 1 signal detection and data handling are simple enough to cover fairly easily a very large set of registrations, which is mandatory in a very long term analysis like the present one. Third, the instrument used during period II was operating reliably for tens of years, hence the problem of intercalibrating results from different instruments is overcome. (The equipment used during period I was demolished in the war of Lapland, 1944). The 30-year-long period II is, to our knowledge, the longest period of Pc 1 pulsations studied with one

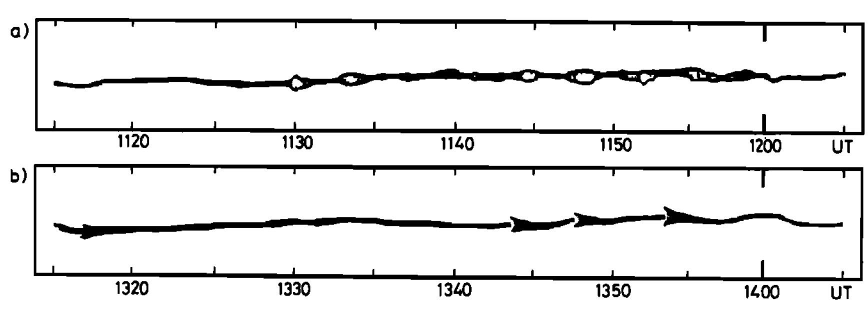

Fig. 1. (a) A typical example of a chain bubbles registered by the Sodankylä quick-run magnetometer system. (b) The nonmicropulsational background mainly consists of the clearly distinguishable arrow-head or wedge-shaped formed signals caused by thunder.

instrument. Most other very long term observations [e.g., *Fraser-Smith*, 1970, 1981] are based on results from more than one equipment and therefore include some kind of intercalibration.

Furthermore, there is very little background from sources other than micropulsations which would cause analogous signals. The main source of background is due to thunder, which, when close enough to the station, can cause mechanical vibrations of the system. Thunder effects occur fairly seldom, mainly during the short Finnish summer, particularly in July and August. Furthermore, the signal caused by thunder is easily distinguishable from the signal of micropulsations because of its very different, typically arrow-head or wedge-shaped form (see Figure 1*b*).

There are, of course, also some drawbacks in the QR method with respect to the standard pulsation magnetometer method. For example, it is clear that no information on the polarization of the Pc 1s can be obtained by this method. Also, as already mentioned above, the QR method cannot distinguish between periodic (structured) and nonperiodic (unstructured) Pc 1s. Furthermore, the QR method cannot distinguish between genuine Pc 1 pulsation events and a number of other types of micropulsations at the same frequency, especially PiBs (bursts of irregular pulsations), PiCs (continuous irregular pulsations), and IPDPs (intervals of pulsations with decreasing period). However, as we will discuss later, comparison of the results from the QR registration and simultaneous pulsation magnetogram measurements verifies that most QR Pc 1 events really are genuine Pc 1 events and that the background from the other types of micropulsations remains fairly small. Particularly, one can increase the percentage of true Pc 1 events by setting a lower limit to the length of the event.

The instrument used during the period II has been fully tested and analyzed [*Kivinen*, 1971], and therefore all of its properties relevant to this analysis are known. For example, the eigenfrequencies of the *H*, *Z*, and *D* components are 0.375, 0.333, and 0.480 Hz, respectively. The amplification curves of all the three components are very sharp, particularly for the *H* component whose half width at half-maximum is only 0.0038 Hz. The corresponding half widths of the *Z* and *D* components are 0.0128 and 0.0098 Hz. The *H* and *D* components are more sensitive than the *Z* component to the pulsations of the magnetic field at their exact eigenfrequencies. The smallest field intensities that can make them resonate observably at their eigenfrequencies are 50 and 60 pT, while the corresponding number for the *Z* component is 140 pT. It is still to be noted that because of the very sharp resonance curves, the minimum resonating field intensities grow very rapidly for frequencies outside the eigenfrequency. For a comparison, the average amplitude of Pc 1 micropulsations at high-latitudes is some 100 pT [*Heacock and Kivinen*, 1972].

The equipment used during the period I was basically similar to the second system but, since it was never tested, many of its properties, for example, the resonance frequencies, are unknown. As we will discuss later, some crude information on these properties can be derived by comparing the results obtained during the first and second period. However, any detailed comparisons between the results from the two periods have to be made with caveat.

3. QUICK-RUN DATA

A great majority of the bubbles in the QR magnetograms appeared in a chain of several bubbles. Such a chain was considered to form an entity as long as any of the two consecutive bubbles were separated by less than half an hour. A typical time gap between two consecutive bubbles in a chain was from a few to 10 min, i.e., clearly less than half an hour. Furthermore, the time gap between two such chains was generally much longer than half an hour. Accordingly, the chosen cutoff of half an hour seemed to be of the correct order of magnitude when gathering the bubbles into separate chains.

If two or three chains of bubbles defined in the above way occurred in the various components simultaneously, overlapping in time within half an hour, they were considered to belong together and to form a unit that we call here an "event." Thus an event can be a separate bubble or a chain of bubbles occurring in one or several components at least partly simultaneously. This definition proved to be very practical, since there was very seldom any doubt as to whether chains in two or three components are really parts of the same phenomenon or not.

For all the three possible components of each registered event we measured the start time of the first bubble in the chain and the length of the chain to an accuracy of 1 min, as well as the width (twice the amplitude) of the broadest bubble in the chain in tenths of a millimeter. The error involved in the time measurement was normally less than 1 min, but the error of the width was relatively larger, approximately 0.2 mm.

In the whole data set there are altogether 1101 events, out of which 342 events occur during the first period and 759 events during the second period. In the first (second) period, 233 (478) events included a signal in the *H* component, 31 (201) in the *Z* component, and 167 (634) in the *D* component. The different relative amount of signals in the two instruments is most probably due to the fact that the instruments had different resonance properties. Judging from the above numbers, in both instruments the *Z* component was less sensitive than the two other components. Most probably it was even less sensitive in the first instrument, relatively, than in the second instrument. On the other hand, the *H* component of the first instrument was more effective than the *D* component in measuring micropulsations, contrary to the second equipment where the *D* component was tested to have a wider amplification curve and thus to be more effective when detecting pulsations.

The minimum, maximum, and average lengths and widths of the chains of the three components are given in Table 1 for the two periods separately. It can be seen there that the differences in the chain widths and, in particular, in the chain lengths are in accordance with what was mentioned above about the known properties of the instrument of period II and the relative occurrence of events in the two instruments. Moreover, as an example, we have displayed in Figure 2 the distribution of the width of the *H* component over the whole data period.

We should also point out that the years 1944, 1953, and 1983 have only partial data coverage and will be dropped out of any quantitative analysis. Furthermore, registrations during the years 1982 and 1983 were much less efficient than in other years, since the equipment was not sufficiently maintained any longer. (They were demolished in 1983.) Therefore results for these 4 years should be treated with due caution and are not taken into account in any detailed calculations.

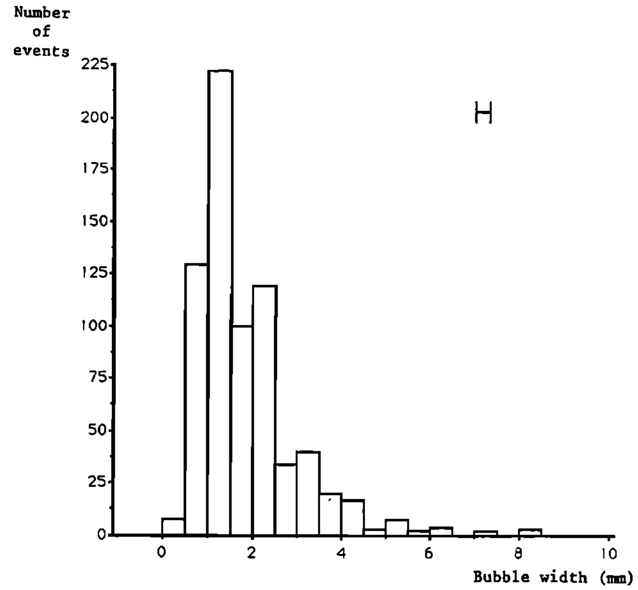

Fig. 2. The distribution of the width of the *H* component over the whole data period. The *x* axis gives the width in steps of 0.5 mm, and the *y* axis gives the corresponding number of *H* component chains with the largest bubble width in that interval. The average width is 1.7 mm.

4. COMPARISON WITH THE PULSATION MAGNETOMETER DATA

In order to further test the reliability of the resonance method we have compared the QR data with the pulsation magnetometer data from 1974 to 1983, i.e., over the period during which both equipment were in function in Sodankylä. Taking the *H* component as an example, we have examined the correctness of all the 144 QR events that include a signal in the *H* component during this period by analyzing the corresponding measurements of the pulsation magnetometer during these events. Out of these events, 91, i.e., 63.2 %, were verified by the pulsation magnetometer to be clear Pc 1 events, 11 events were classified as IPDP micropulsations, 20 events as PiBs or PiCs, and the remaining 22 "missing" QR events were either not detected by the pulsation magnetometer at all or included Pc 1 activity at frequencies not overlapping with the eigenfrequencies of any of the QR components. The group of "missing" events also includes those cases where the timing of the QR Pc 1 event was incorrectly read or coded by the analyzer, so that no micropulsations could be found by the sonogram at the given erroneous time of the QR event.

Interesting differences appeared in the annual distributions between these groups of events. The IPDP events only appeared during the low sunspot years (1974-1977) which is in good accordance with earlier observations [*Maltseva et al.*, 1988]. On the other hand, the number of PiBs and PiCs was almost constant over the years. The "missing" events showed large annual differences but no systematic asymmetry between low and high solar activity. All in all, the number of non Pc 1 QR events was slightly higher during the SS minimum than maximum years. However, during the maximum years the percentage of the non Pc 1 events was very large, and only a small fraction of all QR registered events were found to be pure Pc 1 events. More specifically, out of the 18 QR events during the three SS maximum years 1979-1981 only 3, i.e., 16.7%, were verified by the sonogram to be true Pc 1 events. Correspondingly, for the three minimum years 1975-1977 there were 71

TABLE 1. Properties of the Lengths and Widths of Pc 1 Chains

	Period I			Period II		
	H	*Z*	*D*	*H*	*Z*	*D*
Chain length, min						
Minimum	2	1	3	2	1	1
Maximum	1470	140	600	345	235	400
Average	85	25	69	45	27	54
Chain width, mm						
Minimum	0.5	0.4	0.3	0.4	0.3	0.3
Maximum	8.0	3.5	9.0	8.0	6.5	9.0
Average	1.9	1.0	1.9	1.6	1.3	2.0

The minimum, maximum and average values of the chain lengths in minutes for all the three components and the two data periods and the corresponding properties for the chain widths in millimeters.

verified Pc 1 events out of 96, i.e., 74%. Therefore the relative asymmetry in Pc 1 activity between the three minimum and maximum years increased, rather than decreased, from the ratio 96:18=5.3 given by the QR method to 71:3=23.7 after examination with the pulsation magnetogram.

We have also calculated the durations of the events in the various groups found by the pulsation magnetogram. The total sum of durations of all the 144 *H* component QR events was 114 hours and 51 min. The verified 91 Pc 1 events had an average duration of 67.0 min, much longer than the events of all other groups. The total Pc 1 duration summed up to 101 hours and 40 min, which is already 88.5% of the total duration of all events. The IPDP events had an average duration of 19.0 min and formed 3.0% of the total duration. The PiB/PiC events and the "missing" events made up 4.5% and 3.9% of the total duration and had average durations of 15.7 and 12.2 min, respectively. Therefore, although there is a sizable non Pc 1 event background among the QR events, this background is seen to be of much smaller importance if, instead of event number distributions, one studies the distribution of the total Pc 1 pulsation time by weighing each event with its duration.

Moreover, because of the longer average duration of the true Pc 1 events, one can increase their relative amount very effectively by dropping the shortest events away from the selection. In order to show how effective such a procedure can be, let us now select only those QR *H* component events whose duration is at least 15 min. There are altogether 102 such events with a total duration of 109 hours and 34 min, i.e., still 95.4% of the total duration of all events. Out of these, 83, i.e., 81.4 %, were pure Pc 1 events, 6 IPDP events, 6 PiB/PiC events, and 7 "missing" events. The Pc 1 percentage of the total duration increased up to 92.2%, the IPDP decreased slightly to 2.5%, and the PiB/PiC and "missing" events decreased more dramatically to 3.0% and 2.2%, respectively. Similarly, an even higher lower limit of 30 min renders the QR sample to 63 events with still 83.8% of the total duration. Out of these, 60, i.e., 95.2%, are Pc 1 events, while all other classes include only one event, i.e., 1.6% of the total event number. The Pc 1 events form now 98.6% of the total duration. Thus imposing a lower limit to the event duration effectively increases the relative number of true Pc 1 events.

As an additional example of the good correspondence between the QR and pulsation magnetogram registrations we have studied the Pc 1 event on August 27, 1976. In Figure 3 we have presented the *H* component sonogram intensity in the time-frequency frame showing Pc 1 activity from 0935 to about 1050 UT. (The sonogram of the *D* component is nearly identical. The *Z* component was not measured at all by the pulsation magnetometer system at Sodankylä.) The average frequency is seen to slowly decrease from 0.6 to 0.3 Hz during this period. Below the sonogram we have also given the corresponding times registered by the three components of the QR magnetometer. The QR *D* component shows Pc 1 activity after the pulsation frequency has decreased to the level of its eigenfrequency (0.480 Hz). Later, with the average Pc 1 frequency decreasing, the other QR components with lower eigenfrequencies also register the signal. Correspondingly, the signal disappears first from the *D* component and stays longer in the *H* and *Z* components. Note that the Pc 1 signal is registered in the stiff *Z* component only after a further intensification at low frequencies and that the more sensitive *H* component pulsates longer than the stiffer *Z* component.

We have also studied what is the dominant type of the QR micropulsation events according to the sonogram classification. Making only a rough division into structured (consisting mainly of periodic emissions and whistlers) and unstructured (mainly hydromagnetic chorus) pulsations, we found that the unstructured pulsation events dominate over the structured events

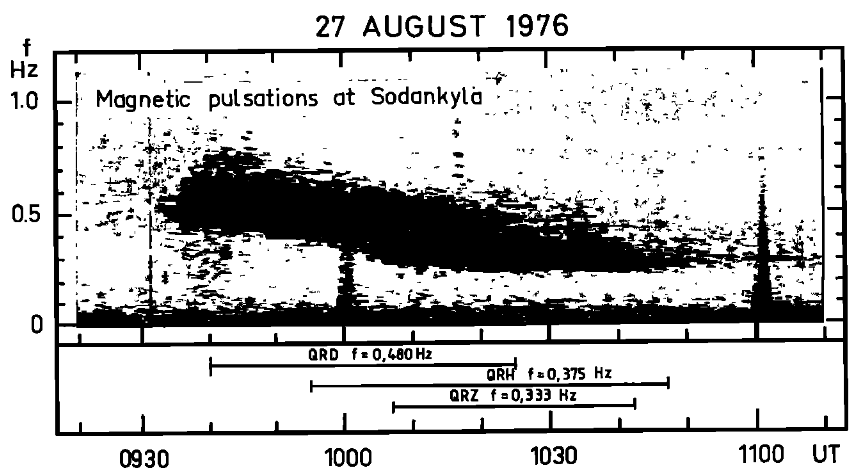

Fig. 3. The sonogram picture showing Pc 1 pulsations observed by the *H* component pulsation magnetometer at Sodankylä on August 27, 1976, from 0935 to about 1050 UT. (The sonogram of the *D* component is nearly identical. The *Z* component was not measured at all by the pulsation magnetometer system at Sodankylä.) The corresponding times of the Pc 1 registrations by the three components of the Sodankylä quick-run (QR) instrument are given as bars below the sonogram together with their eigenfrequencies.

roughly in the ratio of 3.3:1, which is slightly higher than the corresponding ratio of about 2.7:1 at a high-latitude station [*Nagata et al.*, 1980] when using all sonogram events. This difference is naturally explained by the fact that the eigenfrequencies of the QR magnetogram are all below 0.5 Hz, where the hydromagnetic chorus has its average frequency, while the periodic emissions tend to occur at slightly higher frequencies [*Nagata et al.*, 1980; *Fukunishi et al.*, 1981].

5. Long-Term Pc 1 Occurrence: Comparison With Solar Activity

In order to study the very long term behavior of the Pc 1 pulsations we have first calculated the annual number of QR events and presented the ensuing event number distribution together with the annual averaged unsmoothed sunspot numbers in Figure 4. Despite some statistical variations the dominant feature over the whole registration time is the periodic appearance of years of high and low number of Pc 1 events. A typical annual number of QR Pc 1 events during years of high (low) Pc 1 activity is several tens of events (not more than 10 events). The length of the Pc 1 activity cycle seems to be very close to the length of the solar activity cycle. Moreover, the years of highest annual Pc 1 event number fairly closely coincide with lowest sunspot years and vice versa, thus showing a strong negative correlation between the two variables over the whole data period.

A more correct and physical way of studying long-term Pc 1 activity is to take the event duration into account, thus counting the total annual Pc 1 active time. As discussed in the previous section, weighing each event with its duration increases the relative contribution of the longest events that are most probably least contaminated by other than pure Pc 1 events. This procedure also alleviates the possible remaining differences between the analyzers concerning the division of bubble chains into events, which may be partly responsible to the fluctuations in the annual distribution of Pc 1 events.

The annually summed durations of the three components and their sum, as well as the annual sunspot numbers are presented in Figure 5. The cyclic pattern of Pc 1 activity stands out now very clearly, even more so than in Figure 4. The strong negative correlation between the sunspot numbers and the annual Pc 1 durations is

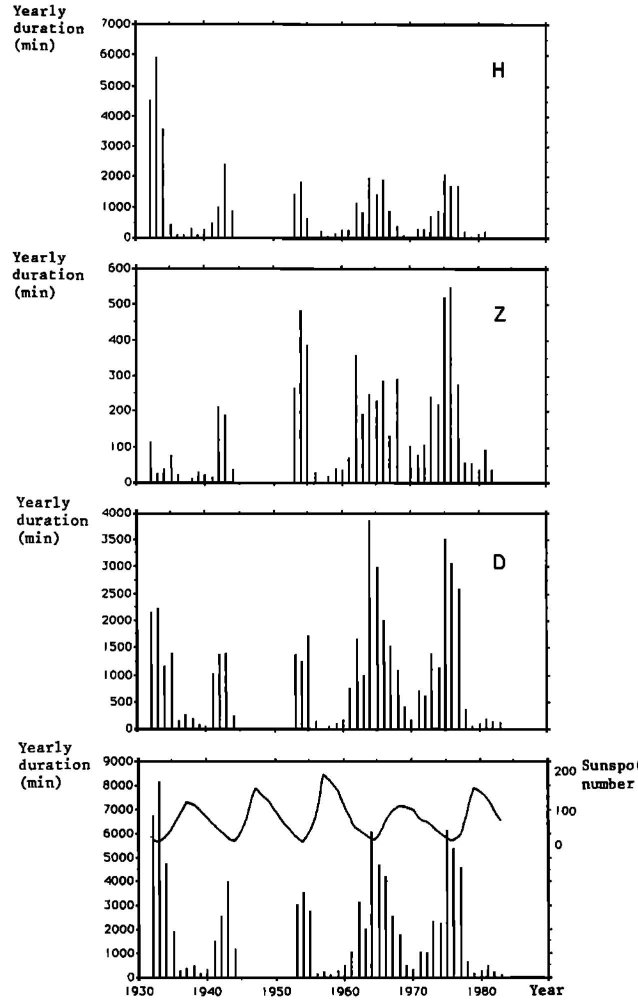

Fig. 5. The annual sums of durations (in minutes) of the QR (top) *H* component, (second) *Z* component, (third) *D* component, and (bottom) all the three components summed. The years with partial data coverage have, for completeness, also been included in the figure. The averaged annual unsmoothed sunspot numbers (solid line) are also shown at the top of the bottom figure with the scale on the right-hand side.

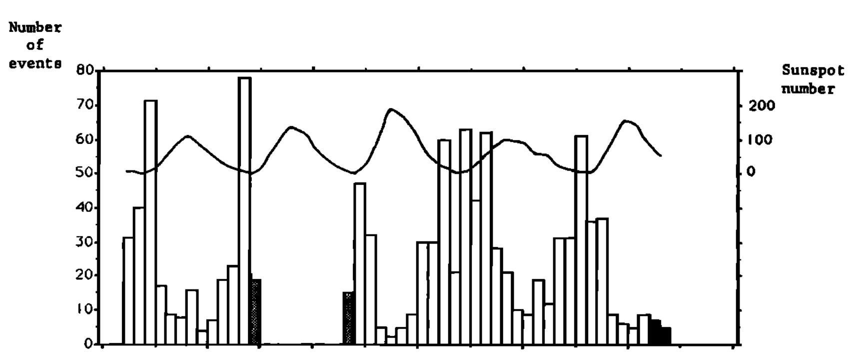

Fig. 4. The annual numbers of the QR Pc 1 events (bars) and the averaged annual unsmoothed sunspot numbers (solid line) over the whole data period 1932-1983. The years with partial data coverage have been marked grey. The Pc 1 event number scale is on the left-hand side of the figure, and the sunspot number scale is on the right-hand side.

evident for all the three components, particularly clearly for the *H* and *D* components which have the largest numbers of events and longest durations of pulsation chains. The differences in the annual Pc 1 activity measured in this way are very large, much larger than found above by counting the number of events. Taking the sum of all components as an example, the QR Pc 1 activity ranges from only a couple of hours in the lowest activity years to more than 100 hours in the most active years.

Figure 5 also demonstrates clearly that, as mentioned earlier, the Pc 1 sensitivities of the three components of the QR system used during period I were greatly different from those of the system used during period II. The *H* component of the first instrument was much more sensitive than the two other components of that instrument or the corresponding component of the second instrument. On the other hand, the *D* component and, particularly, the *Z* component of the first instrument were much less sensitive to Pc 1 activity than the corresponding components of the second instrument.

It is also of interest to compare the two subsequent complete Pc 1 activity cycles measured during period II, i.e., the time from the maximum of solar cycle 19 to the maximum of solar cycle 21. The overall forms of these Pc 1 cycles look fairly similar, and, for example, the highest Pc 1 activity levels during the solar cycle minimum years attain approximately the same values, especially for the dominant *H* and *D* components. However, some interesting differences also appear. For example, the decline of the second complete Pc 1 cycle proceeds much faster, essentially in 1 year from the highly Pc 1 active year of 1977 to the low activity year of 1978, than the more stepwise decline of the first Pc 1 cycle during the years from 1964 to 1970. More quantitatively, taking the sum of all components as an example, while the largest difference in total Pc 1 active time between two subsequent years from 1964 to 1970 is only 1647 min (from 1966 to 1967), the difference between 1977 and 1978 is 3925 min. These pairs of years are exactly those for which the largest increases in the sunspot number during the respective cycles take place. Accordingly, the faster decline of the second Pc 1 cycle seems to be due to the faster rise of solar activity at the beginning of the 21st cycle compared to the slower rise of the 20th solar cycle. Further evidence for such a behavior is obtained from a similar slow (correspondingly, fast) decline in Pc 1 activity during the years 1933-1936 (1955-1956) at the slow (fast) onset of the solar cycle 17 (19).

As another example of the differences between the various Pc 1 cycles, we wish to note that the Pc 1 activity levels around the three sunspot maxima of period II are different and ordered such that, the weaker the maximum is the more Pc 1s are seen at Sodankylä. In order to demonstrate this quantitatively we have studied the three 3 year periods 1957-1959, 1968-1970 and 1979-1981 covering the maximum years of the solar cycles 19, 20, and 21, respectively. The 3 year sums of annual sunspot numbers for these three periods are 534.0, 315.9, and 450.4, and the corresponding sums of 3 year Pc 1 durations are 595, 2492, and 868 min.

The above discussed detailed properties of the various Pc 1 cycles give further evidence about the strong negative correlation between the annual Pc 1 activity and annual solar activity measured by sunspot numbers. This correlation seems to be responsible not only for the very appearance of the Pc 1 cycles but also for many of their small-scale features, which seem to correspond to those of the sunspot cycles. It is therefore evident that the long-term behavior of Pc 1 activity is, to a large part, explained by the solar activity measured by the sunspot number. A possible phase difference between the two cycles cannot be more than a couple of years.

In order to study the validity of the negative correlation in more detail we have made a linear regression analysis for the annual durations of all the three components and also their sum with the annual sunspot numbers and calculated the correlation coefficient R, its square R^2, and the F test probability for the two periods separately, neglecting however the incomplete years 1944, 1953, 1982, and 1983. The results are presented in Table 2. One can see that very large R^2 values (0.6 or higher) are obtained for the two main components (*H* and *D*) for both periods and for the *Z* component of period II. The *Z* component of period I, which has much less statistics than all the other cases, shows considerably smaller correlation. The Fisher F test, which gives the probability for the acceptance of zero correlation hypothesis, shows extremely small values for the second period and very small values also for the *H* and *D* components of the first period, much less than the generally used critical value of 0.01.

In Table 2 we have also calculated the same factors for the cases where the Pc 1 distributions are shifted by 1 or 2 years earlier (-1 and -2) or later (+1 and +2). This is done in order to see what the correlation would be if we had found that the Pc 1 distributions were shifted in the prescribed way. One can see in Table 2 that, when shifting the Pc 1 distributions to earlier times, all the correlations get sizably smaller after 1 year and very much smaller after 2 years. This means, for example, that it is improbable that the Pc 1 maxima would occur earlier at all, and *it is very unlikely that they would occur more than 1 year earlier, i.e., during the declining phase of the sunspot cycle*. Similarly, when shifting the Pc 1 distributions by 1 or 2 years later, all correlations except the *Z* component of the first period get smaller, mostly even faster than when shifting the distributions the other way. The correlation of the *Z* component of period I reaches its maximum 1 year later, but even there the probability does not reach the statistically significant acceptance level, showing that this difference is most probably an error due to the very small statistics.

TABLE 2. Correlation Between the Annual Pc 1 Durations and the Sunspot Number

	Period I			Period II		
	R	R^2	$p(F)$	R	R^2	$p(F)$
All components						
-2	-0.465	0.216	0.1274	-0.496	0.246	0.0073
-1	-0.721	0.520	0.0082	-0.725	0.526	$1 \cdot 10^{-5}$
0	-0.842	0.708	0.0006	-0.821	0.675	$9 \cdot 10^{-8}$
+1	-0.752	0.566	0.0048	-0.589	0.347	0.0010
+2	-0.388	0.15	0.2133	-0.114	0.013	0.5621
H component						
-2	-0.439	0.192	0.1539	-0.496	0.246	0.0073
-1	-0.658	0.434	0.0199	-0.704	0.496	$3 \cdot 10^{-5}$
0	-0.776	0.602	0.0030	-0.793	0.630	$5 \cdot 10^{-7}$
+1	-0.701	0.491	0.0112	-0.578	0.334	0.0013
+2	-0.351	0.123	0.2632	-0.092	0.008	0.6411
Z component						
-2	-0.077	0.006	0.8127	-0.455	0.207	0.0150
-1	-0.362	0.131	0.2477	-0.681	0.464	$7 \cdot 10^{-5}$
0	-0.532	0.283	0.0747	-0.774	0.599	$1 \cdot 10^{-6}$
+1	-0.569	0.324	0.0533	-0.544	0.296	0.0028
+2	-0.498	0.248	0.0996	-0.047	0.002	0.8136
D component						
-2	-0.480	0.230	0.1146	-0.471	0.222	0.1133
-1	-0.775	0.600	0.0031	-0.700	0.490	$3 \cdot 10^{-5}$
0	-0.877	0.770	0.0002	-0.795	0.631	$4 \cdot 10^{-7}$
+1	-0.757	0.573	0.0044	-0.566	0.321	0.0017
+2	-0.397	0.157	0.2016	-0.131	0.017	0.5076

The correlation coefficient R, its square R^2 and the F test probability for the two periods (years 1944, 1953, 1982, and 1983 not included) for the correlation between the annual sunspot number the annual QR Pc 1 durations (sum of all the three components and the components separately). The numbers on the left-hand side of the table indicate that the Pc 1 distribution is as observed (0) or has been shifted by 1 or 2 years earlier (-1 and -2) or later (+1 and +2) with respect to the sunspot numbers.

6. Comparison With Other Long-Term Pc 1 Observations

Our results verify and extend the earlier observation by *Kawamura et al.* [1983] (also verified by *Pikkarainen et al.* [1987]) about the approximate inverse relation between the annual Pc 1 and solar activity at high latitudes. Kawamura et al. divided the Pc 1 pulsations into four main groups: periodic and irregular emissions, hydromagnetic chorus and Pc 1-2 band. Kawamura et al. found that the largest annual Pc 1 activity for periodic emissions was found in 1976 but for the three other groups in 1977. Since our QR instrument registers the low frequency range approximately between 0.3 and 0.5 Hz where the dominant contribution comes from the hydromagnetic chorus [*Fukunishi et al.*, 1981; *Kuwashima et al.*, 1981], this may be in slight contradiction with our maximum appearing in 1975. However, since all the years from 1975 to 1977 are very active and the difference in the annual Pc 1 active time between 1975 and 1977 is relatively small, no real controversy exists between the two results.

Notwithstanding the small differences in the details, the results obtained by *Kawamura et al.* [1983] (also verified by *Pikkarainen et al.* [1987]), using pulsation magnetometers covering the whole Pc 1 frequency range, verify that the anticorrelation persists for the bulk of all the Pc 1 events at a high-latitude station and not just a small low-frequency fraction of them. Therefore the anticorrelation between the sunspot number and the number of Pc 1 events measured by the QR method cannot, for the main part, be due to the average Pc 1 frequency changing over the solar cycle. (Of course, it is still possible that a small high-frequency part may behave differently from the bulk of the events.) In Figure 6 we have compared our results from high latitudes with the two longest series of observations of Pc 1 pulsations from the mid-latitude stations in Soviet Union [*Troitskaya*, 1967; *Matveyeva*, 1987] ($L=2.3$) and California [*Fraser-Smith*, 1970, 1981] ($L=1.9$). In large features all observations show an approximate inverse relation with the sunspot cycle. There are also some common detailed features between the high- and mid-latitude Pc 1 occurrences which have not been noted before. Many of the differences in Pc 1 activity from one cycle to another, which were already discussed above on the basis of our QR results, are recognizable in the mid-latitude results also. For example, the level of Pc 1 activity during the three maxima of solar cycles 19, 20, and 21 is ordered exactly the same way in the Soviet mid-latitude station as in Sodankylä, i.e., the more active the solar cycle

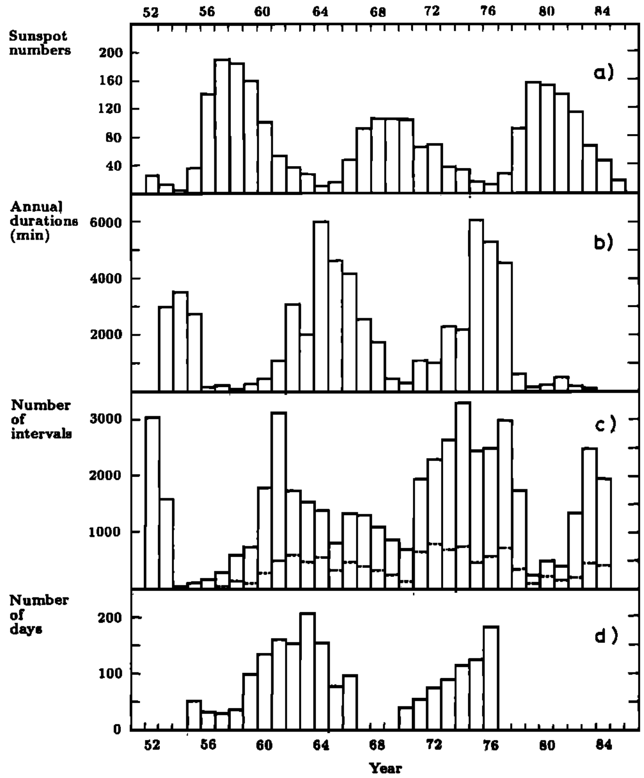

Fig. 6. (a) The averaged annual unsmoothed sunspot numbers from 1952 to 1985. (b) The annual sums of durations (in minutes) of all the three QR components summed. The years with partial data coverage have been marked grey. (c) The number of 15 min intervals of periodic Pc 1 emissions observed at Alma Ata in 1952-1958 [*Troitskaya*, 1967] and at Borok in 1959-1984 [*Matveyeva*, 1987] after normalization into the same scale. The dotted bars give the corresponding number for the lowest frequency (T=2-3 s) emissions. (d) The annual number of Pc 1 active days at California in 1955-1966 [*Fraser-Smith*, 1970] and 1970-1976 [*Fraser-Smith*, 1981].

maximum is, the less of Pc 1 pulsations there are. This fact is even more clearly to be seen in the Soviet results than in our QR measurements. Unfortunately, the Californian observations are missing in critical years and do not allow another independent comparison.

Another common fact for high-latitudes and mid-latitudes, which was observed and discussed above based on the QR observations, is that the decline of the Pc 1 activity during the start of a new solar cycle seems to be dependent on the steepness of the rise of the new solar activity. This can be verified by the Soviet mid-latitude observations particularly clearly for the very slow decline during the start of the solar cycle 20 and the much more abrupt decline of the next Pc 1 cycle. The Californian observations give a hint of a similar slow decline during the start of the solar cycle 20 at the same time, although, again, crucial years are missing. The most significant difference between the high- and mid-latitude results seems to be that the Pc 1 activity is relatively larger during the declining phase and before the end of the solar cycle at the mid-latitudes than at the high latitudes. This is exemplified by the fact that the Soviet stations find their maxima 1-3 years before the solar cycle minimum times and that their Pc 1 distribution is consistently asymmetric with respect to the solar cycle minimum in favor of the declining phase. The latter is true also for the Californian station around the minimum between 19th and 20th solar cycle.

The differences between the Soviet and Californian observations have been discussed earlier to a large extent [e.g. *Fraser-Smith*, 1970]. Without going here into that discussion in much more detail we would just like to pay attention to the frequency dependence of the Soviet observations [*Matveyeva*, 1987], see also Figure 6*c*. The division of the pulsations into high (T=0.3-0.5 s), medium (T=0.6-1.5 s), and low (T=1.6-2.0 s) frequency ranges has revealed that there are dramatic differences in the long-term behavior of the Pc 1 pulsations with different frequencies. While, for example, particularly the highest-frequency pulsations seem to be responsible for the peaks during the early declining phase of the uneven solar cycles (particularly in 1961 and 1983), the lowest frequencies show a much broader maximum closer to the solar cycle minimum.

The observation of a frequency dependence of the long-term Pc 1 variation at mid-latitudes [*Matveyeva*, 1987] is a very important finding and might, together with the differences in the pulsation counting procedures, be able to explain the differences between Soviet and Californian observations. The frequency range of the Californian stations is between 0.4 and 3 Hz, but the frequency distribution of the pulsations, or even the average frequency is not known to us. Furthermore, the Californian results have been obtained by normalizing the consecutive observations of two instruments with different dynamic properties. It may therefore be difficult, if not impossible, to finally solve the question of the origin of the differences between these two long-term mid-latitude observations.

The large differences in Pc 1 activity between the even and uneven solar cycles led *Matveyeva* [1987] to propose a 22-year cycle as the fundamental period for long-term Pc 1 occurrence. Our results do not support this hypothesis but, instead, show a very similar behavior over nearly four solar cycles and a fairly direct negative response of the Pc 1 activity to solar activity. However, these two observations may not necessarily be contradictory in view of the fundamentally different properties of Pc 1 pulsations at low and high latitudes.

The connection of the periodic Pc 1 emissions with the storm evolution [*Wentworth*, 1964; *Plyasova-Bakunina and Matveyeva*, 1968; *Kuwashima et al.*, 1981] is most probably responsible for the larger amount of high-frequency Pc 1s during the declining phase at low latitudes and mid-latitudes, since the source region of periodic emissions is at lower latitudes after large storms. The fact that this behavior is more pronounced during the decline of the uneven solar cycles is explained, according to *Matveyeva* [1987], by the observation [*Zaretskiy et al.*, 1983] that the number of flare storms is larger during the decline of an uneven cycle than an even cycle. Moreover, ionospheric damping must also be a very significant factor for the long-term Pc 1 activity at low- and mid-latitude stations since, for example, the diurnal distribution prefers postmidnight hours (see, for example, *Kuwashima et al.* [1981], closely following the minimum ionization times of the ionosphere [*Strestik*, 1981].

On the other hand, the dominant form of Pc 1 pulsations at high latitudes, the hydromagnetic chorus, is independent of the storm time development [*Kuwashima et al.*, 1981]. Therefore it is probable that its origin is completely different from that of the periodic emissions of low-altitudes and mid-altitudes. Furthermore, the diurnal distribution of the hydromagnetic chorus is pronouncedly peaked in the midday - early afternoon hours [*Fukunishi et al.*, 1981; *Kuwashima et al.*, 1981], which is in dramatic difference to the ionospheric dependence observed at low-latitudes and mid-latitudes.

7. CONCLUSIONS

In this paper we have introduced and examined an old but rarely used resonance method with which it is possible to study the very long term occurrence of Pc 1 micropulsations. The method allows detection of Pc 1 pulsations with large enough amplitudes and a frequency close to the eigenfrequency of the magnetometer system. The eigenfrequencies of the three components of the quick-run magnetometer system used at the high-latitude station of Sodankylä covered the frequency range from about 0.3 to 0.5 Hz.

We have carefully analyzed the data obtained by the resonance method by comparing them with the sonogram results over an extensive period from 1974 to 1983. Irrespective of the background from other types of micropulsations, the correspondence between the data from the two methods was good. Furthermore, by weighing the QR Pc 1 events with their durations one could significantly reduce the interference of this background.

Our analysis extends over the whole registration period in Sodankylä from 1932 to 1944 and from 1953 to 1983, i.e., covering nearly four solar cycles. The results show a very strong negative correlation between the annual Pc 1 activity and the annual sunspot number which persists over the whole data period. According to the statistics obtained, it is, for example, very unlikely that the Pc 1 activity maximum at a high-latitude station would occur more than at most 1 year away from the sunspot minimum year. Furthermore, as a result of the negative correlation, some of the differences between the various sunspot cycles can be seen in the corresponding cycles of annual Pc 1 activity.

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