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VARIATIONS IN THE GEOMAGNETIC FIELD AND AURORAL-ZONE X-RAY INTENSITY IN THE Pi 1 PERIOD RANGE

by

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Abstract

Simultaneous balloon-borne x-ray measurements and earth current recordings from Sodankylä ($L = 5.2$) have been analysed. It has been concluded that the pulsation characteristics in the midnight sector of the auroral zone are intimately related to the acceleration and precipitation mechanisms during auroral substorms associated to the auroral electrojet. On the other hand, the *Pi* 1 micropulsation activity during the substorm recovery and toward the morning sector of the auroral zone is correlated to the low-energy electrons drifting in the geomagnetic field. Simultaneous particle pulsations are only weakly dependent on micropulsation intensity.

1. *Introduction*

Many auroral-zone phenomena are closely associated with the development of the magnetospheric substorm. Also the processes controlling the pulsation characteristics of some phenomena (auroras, x-rays, magnetic field) seem to be effective only during substorms (see the review papers 36, 31, 14, 10 and 19). It is widely believed that particle pulsations are mainly due to the modulation effect of micropulsations upon magnetospheric particle fluxes. However, the precise nature of this interaction has not been experimentally determined.

Geomagnetic micropulsations are classified in two types termed *Pc* and *Pi*. The *Pc* pulsations are regular and continuous in character whereas the *Pi* pulsations have more irregular waveforms, *i.e.* broad band frequency characteristics. (For the detailed discussion, see 18, 19.) One of the most interesting differences between these two classes is the fact that only *Pi* pulsations are intimately related to the substorm activity (except for the special *Pc* type that is termed »IPDP») although the *Pc* pulsations are also affected by magnetospheric disturbances.

Auroral luminosity and x-ray pulsations are seldom very regular and they seem to persist for a shorter time than micropulsation events (26). No classification has been applied on particle pulsations. However, the period of particle pulsations, on the average, increases from the midnight sector of the auroral zone towards the noon sector (32). Usually, particle and geomagnetic pulsations have power in the same frequency range.

Several theories of *Pi* micropulsations have been proposed (17). It is obvious that *Pi* 1 is closely associated with the magnetospheric electron dynamics. According to observations the source mechanisms for both particle and field pulsations may operate close to the ionosphere or far out in the magnetosphere (17 and references therein). Thus it seems possible that at least two generation mechanisms should be identified.

In this paper, auroral x-ray pulsations and geomagnetic micropulsations in the *Pi* 1 period range are studied. General characteristics of the auroral-zone electron precipitation phenomena are given together with pulsation characteristics in order to find the association between the substorm and pulsation activity. Covariations in geomagnetic field and x-ray intensity are discussed in searching for the generation mechanisms and source regions of auroral-zone pulsations.

2. *Methods of analysis*

X-ray measurements presented in this paper have been made by balloons launched at Ivalo ($L = 5.7$) in 1965 and at Sodankylä ($L =$

5.2) in 1966—67 and 1970 as a part of the coordinated SPARMO program. Plastic balloons of about 5000 m^3 volume were used to carry the payloads to the altitude of 5—10 mb. They usually drifted to the west from the launching site as the measuring campaigns took place in summertime. Thus the observations presented in this study have been made between the L-values 5 and 6. The results of these measurements can be found in Ehmert *et al.* [13], Wilhelm *et al.* [40], Saeger *et al.* [35] and Lukkari *et al.* [25].

Only the flights with a NaI-scintillation counter are used in this study. These flights have been analysed using the highest possible time-resolution. Sodankylä earth current recordings have been analysed for the same intervals. The main interest is in variations in the period range of 1—40 seconds.

The analysis has been made on the basis of 15 minutes intervals coinciding with the intervals for which the magnetic Q-index has been determined at Sodankylä Geophysical Observatory [24]. The Q-index is a logarithmic measure of the maximum deviation of the horizontal magnetic field intensity during a time interval of 15 minutes. It takes values in the range 0 to 11, and in the present analysis the greatest value was 7. The distribution of Q-values in the present study is shown in Figure 1 where the medians and quartiles of Q for the LT hours 2300—1200 are given. As the balloon flights have been performed on the basis

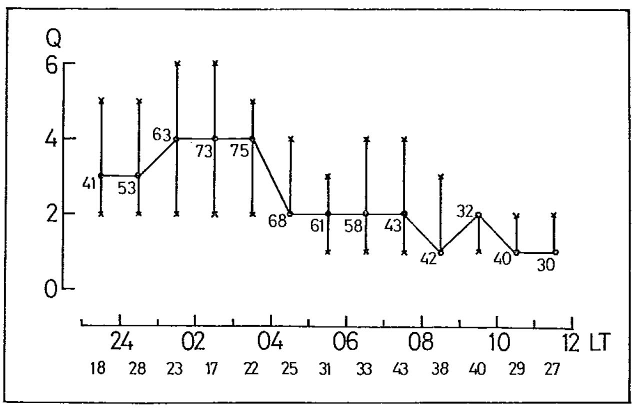

Fig. 1. The median and quartiles of the Sodankylä Q-index as a function of local time. The numbers close to the curve and below the abscissa give here and in subsequent figures the number of data points when the measured quantity > 0 and $= 0$, respectively.

of forecasts, all results presented in this study are for a moderate disturbance level of auroral-zone activities. From its definition we see that the Q-index may be considered as a measure of the intensity of the local overhead auroral electrojet activity.

The x-ray intensity XINT for a given interval is defined as the maximum in the set of values obtained by averaging the 25 keV channel over one minute intervals. The cosmic ray background intensity was always subtracted.

The micropulsation analysis has been based on the strip chart recordings of the earth current activity made at Sodankylä. The maximum amplitude PIAMP 1 and the dominant period T 1 within the minute of the maximum x-ray intensity as defined above have been determined. Also the maximum amplitude PIAMP 2 and the corresponding period $T2$ occurring during the whole 15 min interval have been estimated. The amplitudes have been corrected according to the frequency-amplitude response curve of the earth-current registration system. It appears that the amplification factor does not change very much from $T = 1$ sec to $T = 10$ sec. Above $T = 10$ sec it increases in a more pronounced way. It should be noted here that due to unfortunate difficulties in registration the micropulsation data for the year 1967 was not available for the present study.

On the basis of the high-resolution analysis the maximum values XMAX 1 and XMAX 2 and minimum values XMIN 1 and XMIN 2 of the x-ray intensity were determined for the times of PIAMP 1 and PIAMP 2, respectively. Relative amplitudes XAMP 1 and XAMP 2 of x-ray pulsations are defined as

$$\text{XAMP 1} = 100 \times \frac{\text{XMAX 1} - \text{XMIN 1}}{\text{XMAX 1} + \text{XMIN 1}}$$

and

$$\text{XAMP 2} = 100 \times \frac{\text{XMAX 2} - \text{XMIN 2}}{\text{XMAX 2} + \text{XMIN 2}} .$$

As the resolution of the x-ray analyzer used here decreases toward low intensities (28) the high-resolution analysis is limited to the cases where XINT ≥ 40 cts/sec. The x-ray data from the 1965 flights were excluded from this analysis due to a high scaling factor used during these flights.

The medians and quartiles were calculated for the non-zero values of parameters defined above as a function of local time and local Q-index. Mutual correlations were also studied.

The study was limited to the local time interval from 2300 to 1200 where the most precipitation events were observed. This interval was divided, for some parts of the studies, into four sub-intervals: $2300 \leq LT < 0200$, $0200 \leq LT < 0500$, $0500 \leq LT < 0800$ and $0800 \leq LT < 1200$. In the following presentation only the parameters PIAMP 1, T 1, and XAMP 1 will be discussed as the parameters PIAMP 2, T 2 and XAMP 2 have been found to behave essentially in the same way, respectively.

3. *General characteristics of electron precipitation phenomena*

In their well-known paper, HARTZ and BRICE [16] show that auroral-zone electron precipitation phenomena may be roughly divided into two separate classes: those occurring along the auroral oval and having their maximum around local midnight and those occurring along the circular zone and having their maximum in the morning side of the auroral zone. The two types of precipitation events overlap more or less in the midnight sector. They seem to have different energy spectral characteristics and actually a diurnal energy variation of precipitated electrons has been observed [3, 15].

In Figure 2 the hourly meadian values of the x-ray intensity ($E > 25$ keV) XINT are presented as a function of local time. Two maxima appear: one around the local midnight and another around 06—08 LT. The first maximum is somewhat higher than the second one. The minimum at 04—05 LT might be an indication of the transition region between the auroral zone and oval.

Electron precipitation events in the auroral zone are closely associated with the magnetospheric substorm. Their amplitude can well be taken as measure of the substorm activity as shown in Figure 3. It is seen that XINT is strongly increasing with the Q-index. It is now realized that the precipitation around midnight is associated with the acceleration of auroral particles occurring close to the auroral electrojet whereas the precipitation events in the morning sector are related to the drifting electrons having their source around the midnight meridian (see *e.g.* [38, 22]). This is well illustrated in Figure 4 where it is seen that the precipitation around midnight is almost exclusively associated with a high electrojet activity. It seems that the precipitation occurs there

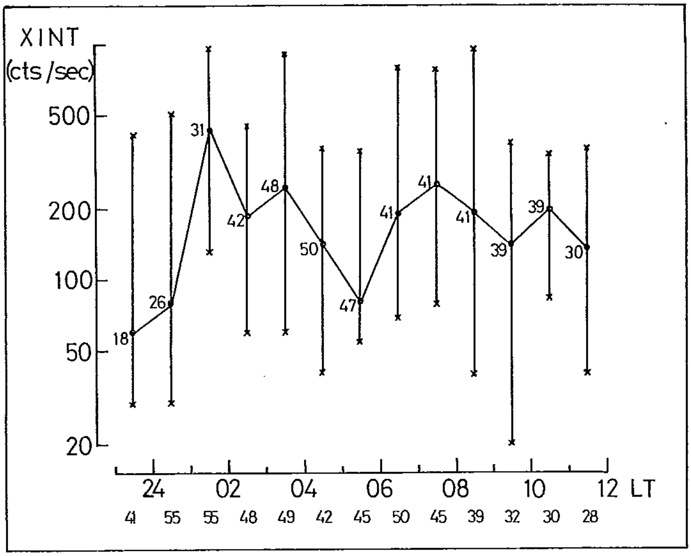

Fig. 2. The median and quartiles of the x-ray intensity ($E > 25$ keV) XINT as a function of local time.

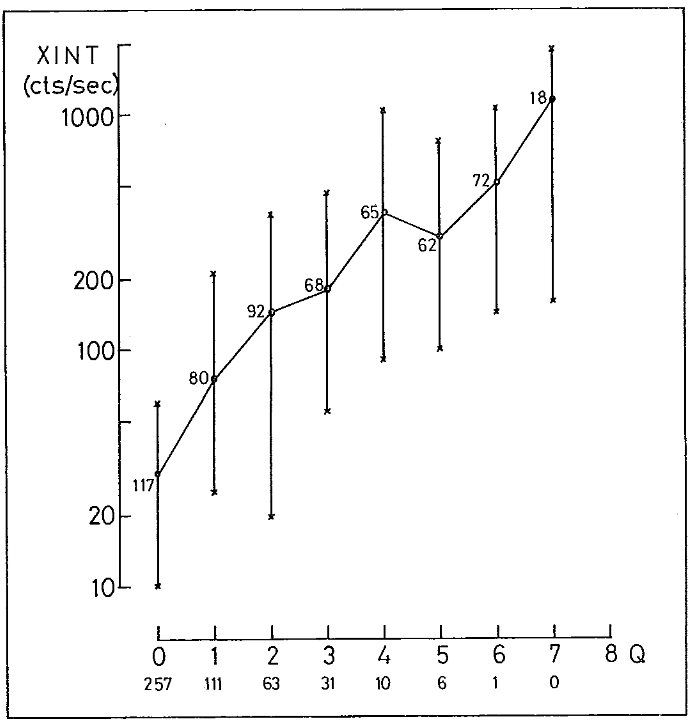

Fig. 3. Variation in the x-ray intensity XINT with the Sodankylä Q-index.

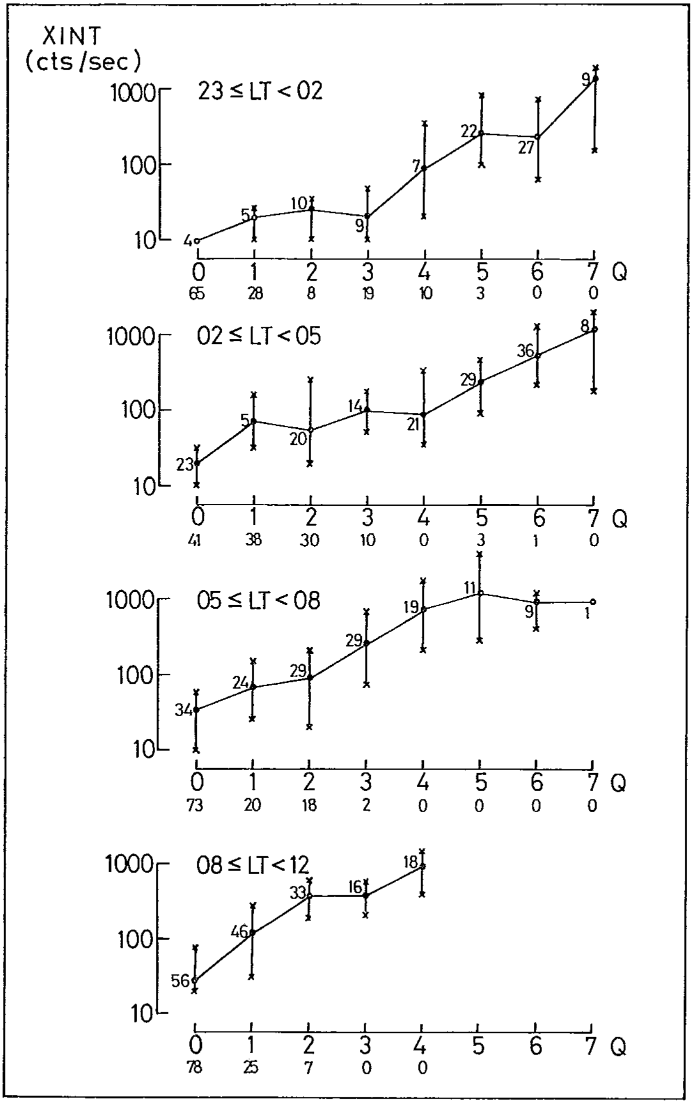

Fig. 4. The same as in Fig. 3 for different local time sectors.

mainly during $Q \geq 4$ which indicates the limit when the direct precipitation can be observed at the Sodankylä latitude. Later, in the course of the morning hours, precipitation events during $Q < 4$ become more and more intense. These events should be considered as the secondary effects of the direct acceleration in the midnight sector through the gradient and curvature drift in the geomagnetic field. A similar importance for $Q = 4$ at Sodankylä has also given by OKSMAN [29] in his study on the r-type sporadic E-layer.

4. *Rapid variations in auroral-zone x-ray intensity*

Post-breakup x-ray events often exhibit irregular pulsations in the period range of 5—30 seconds. Variations are sometimes associated with an energy dependent modulation [6, 20, 32]. The modulation has often been found to operate close to the equatorial plane [34, 7, 8] but it is interesting to note that pulsation amplitudes in precipitated fluxes have been observed to be greater than those in trapped fluxes [33]. Fast pulsations seem to occur more often in the southern part of the auroral zone [2]. Pulsation characteristics mentioned here for x-rays are quite typical also for auroras [30, 31]. It seems possible that pulsation mechanisms are most effective in a limited range of electron energies as discussed in HESSLER *et al.* [17] (see also [39]).

In the present study, we have been interested mainly in the amplitudes of x-ray fast pulsations. In Figure 5 the relative amplitude XAMP 1 is presented as a function of local time. It is clearly seen that the amplitude is increasing towards the morning hours. This is in a good agreement with the auroral observations by KVIFTE and PETTERSEN [23].

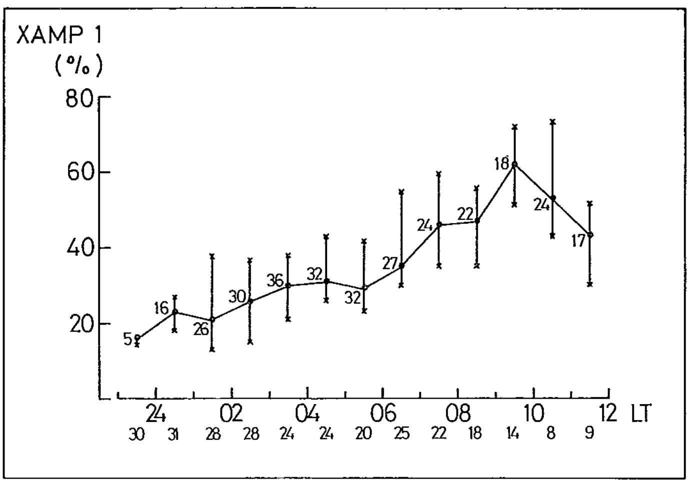

Fig. 5. The median and quartiles of the relative amplitude of x-ray pulsations XAMP 1 as a function of local time.

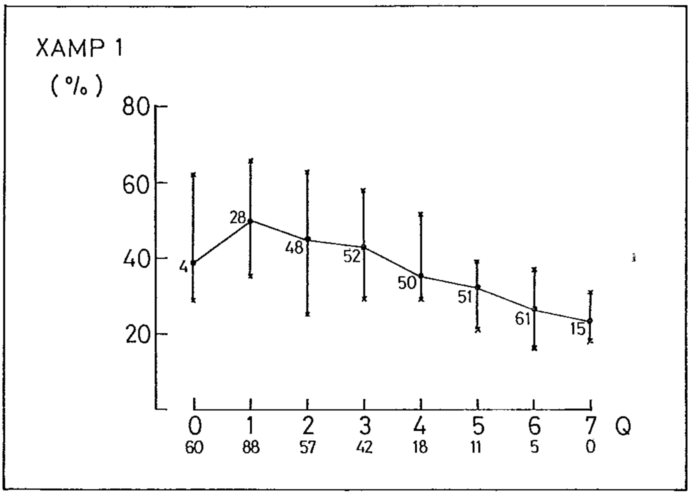

Fig. 6. The relative amplitude of x-ray pulsations XAMP 1 as a function of the Sodankylä Q-index.

In Figure 6 XAMP 1 is shown as a function of the Sodankylä Q-index. It is obvious that the pulsation mechanism is most effective during low Q-values. This indicates again that the particle pulsation activity occurs mainly equatorwards from the main auroral activity. The same tendency has been found in all local time sectors except the midnight sector where the lack of data for low Q-values does not allow us to make any definite conclusions.

In the present study no good correlation has been found between the x-ray pulsation amplitude and x-ray intensity. Only in the midnight sector does the XAMP 1 seem to be in some way dependent on x-ray intensity, in particular for the events $Q > 5$ there is a significant positive correlation. This may be compared with Brekke's statement [4] that auroral pulsations and auroral absorption seem to be completely independent except for perhaps some short periods around midnight.

5. *Observations of the Pi 1 characteristics using earth current measurements*

Recently, many aspects of *Pi* 1 micropulsations have been studied by Hessler *et al.* [17]. On that paper, the *Pi* 1 amplitudes were only briefly discussed. It was found that the intensity of short-period micropulsations increases more rapidly with magnetic activity than that of

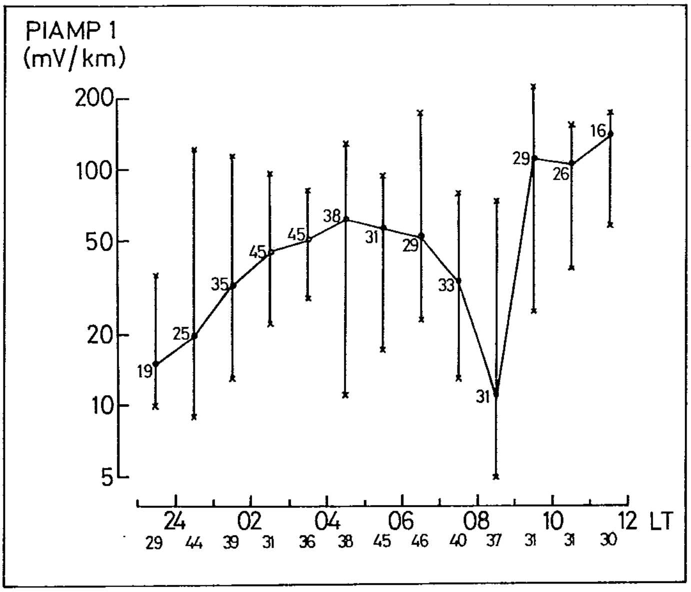

Fig. 7. Local time variation in the *Pi* 1 amplitude PIAMP 1.

long-period micropulsations. It was also noted that the *Pi* amplitude does not seem to be highly correlated to the local magnetic activity.

According to the present analysis, the *Pi* 1 amplitude PIAMP 1 varies with local time as shown in Figure 7. This curve is very similar to the curve presented in Figure 5 where the local time variations of XAMP 1 are shown, except for a pronounced minimum around 08 LT. The increase in *Pi* 1 amplitude after 09 LT is related to the appearance of longer period pulsations, obviously *Pc* 2—3 pulsations, at that time, as illustrated in Figure 8. From Figure 8 we note that *T* 1 does not vary much until 09 LT and therefore the form of the amplification curve of the registration system discussed previously cannot be a significant effect.

The *Pi* amplitude is seen to vary in an interesting way as a function of the *Q*-index, Figure 9. It decreases until $Q = 3$ but after that it increases continuously. Data have been further analysed in different local time sectors as shown in Figure 10. From this figure it is clear that the behaviour of the PIAMP 1 as a function of the *Q*-index changes systematically from the midnight sector to the morning sector: around midnight the dominant *Pi* activity is associated with high *Q*-values but

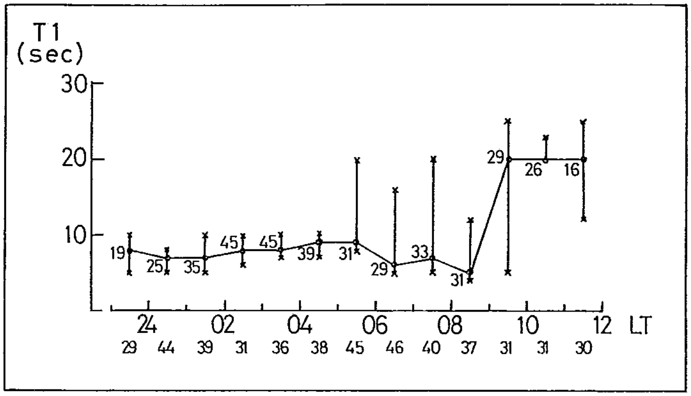

Fig. 8. Observed changes in the *Pi* 1 period *T* 1 as a function of local time.

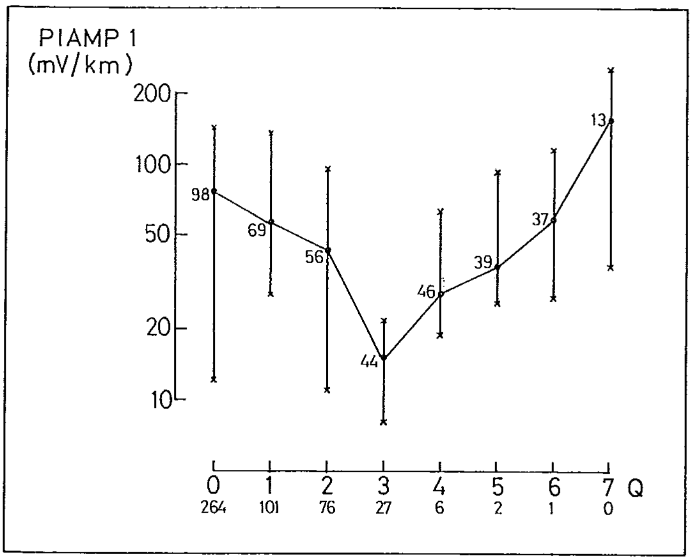

Fig. 9. Variation in the *Pi* 1 amplitude PIAMP 1 at Sodankylä with local magnetic activity as measured by the *Q*-index.

later in the morning *Pi* amplitudes during low *Q*-values are relatively more pronounced than during high ones.

The same conclusions as above can be made also on the basis of correlation analysis. It shows that a significant positive correlation between the PIAMP 1 and XINT in the midnight sector exists for high

Q - values ($Q \geq 4$) whereas later in the morning it may even be negative for the same Q-values. On the contrary, during low Q-values a fairly close correlation seems to exist in the local time sector 05—08 LT.

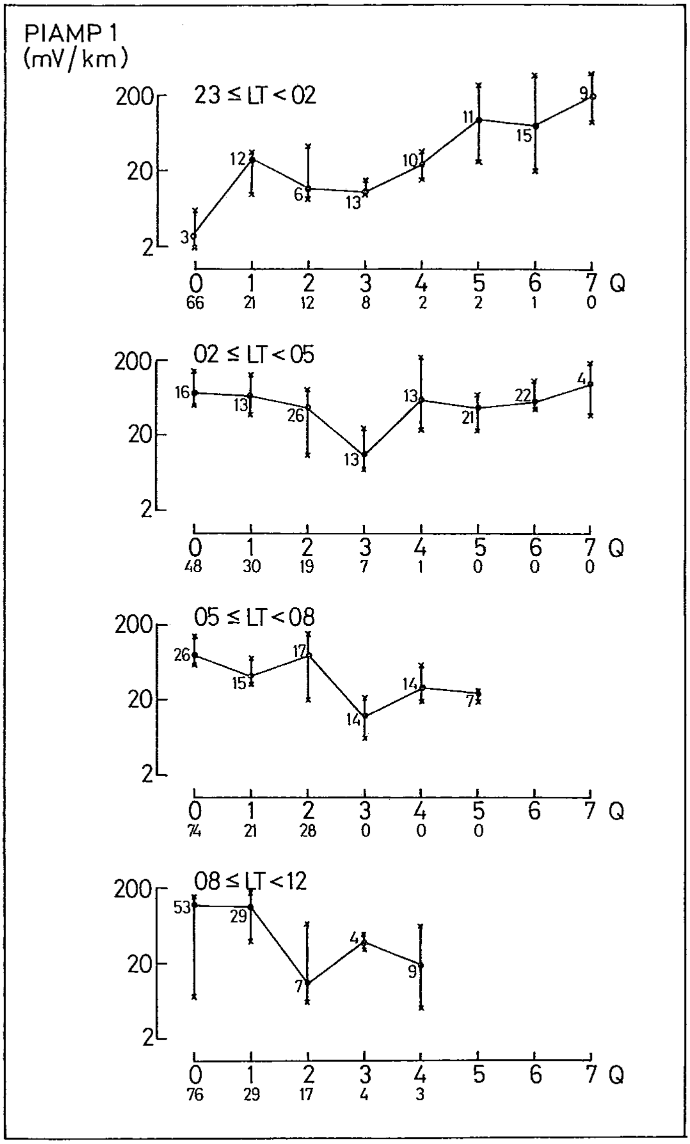

Fig. 10. The same as in Fig. 9 for different local time sectors.

6. *Covariations in the geomagnetic field and auroral-zone x-ray intensity in the Pi 1 period range*

When studying the covariations in the geomagnetic field and x-ray intensity much attention should be paid to some experimental limitations in an analysis of this nature (26). First of all, the viewing areas of recording systems are different. The area of integration for the omnidirectional x-ray detector used here is approximately 150 km in diameter at the altitude of 100 km whereas a more extended area is usually believed to be scanned in magnetic measurements. Since it is known that coherent particle pulsations occur over a region of the order of 100—150 km [32] it may be expected that modulated electron precipitation is occurring within the region of sensitivity of the magnetometer but not be observed by the balloon-borne x-ray detector. Besides this limitation the different propagation properties of particles and waves in the geomagnetic field and the drift of the balloon from the launching site should be taken into account in the study of simultaneous field and particle pulsations.

From two preceding sections we conclude that the correlation between simultaneous *Pi* micropulsations and x-ray pulsations changes with local time and local magnetic activity. A significant positive correlation between field and particle pulsation amplitudes was found only for the intervals of high *Q*-values in the midnight sector. Elsewhere the correlation coefficient was close to zero. This lack of correlation cannot be only due to the limitations in the method employed here as the *Pi* amplitude in the morning sector is much better related to the precipitation intensity than the x-ray pulsation amplitude as discussed in two previous sections. This reasoning is further confirmed by the observation that x-ray pulsations of large amplitudes sometimes occur without any measurable *Pi* activity at Sodankylä which is not expected after the considerations at the beginning of this section. It should be noted here that during these events some *Pi* activity can be identified in the earth current recordings at Kiruna.

Changes in the relation between micropulsation and x-ray pulsation amplitudes can be seen again in Figures 11 and 12 where the ratio between simultaneous *Pi* and x-ray pulsation amplitudes is presented as a function of the Sodankylä local time and *Q*-index, respectively. It appears from these figures that the pulsation power in the midnight sector is exhibited in a more pronounced way in micropulsation activity whereas later in the morning the power in particle pulsation activity is becoming more dominant.

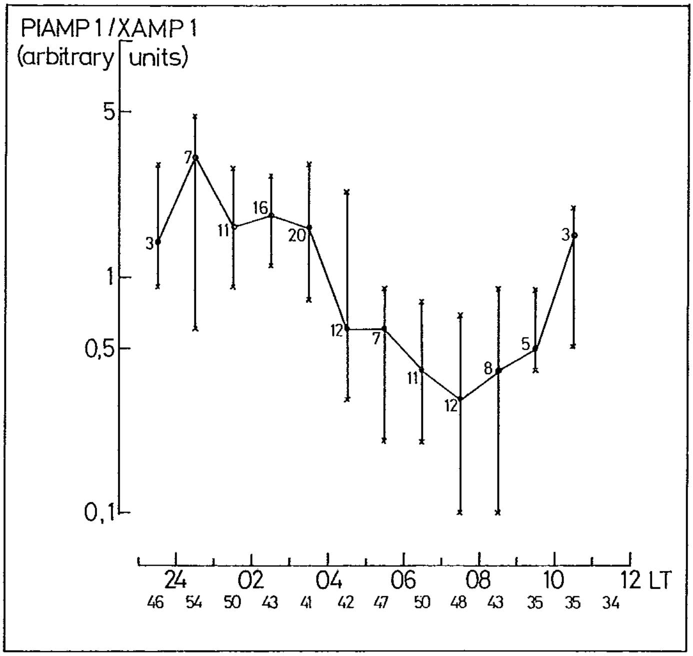

Fig. 11. The median and quartiles of the quantity PIAMP 1/XAMP 1 as a function of local time.

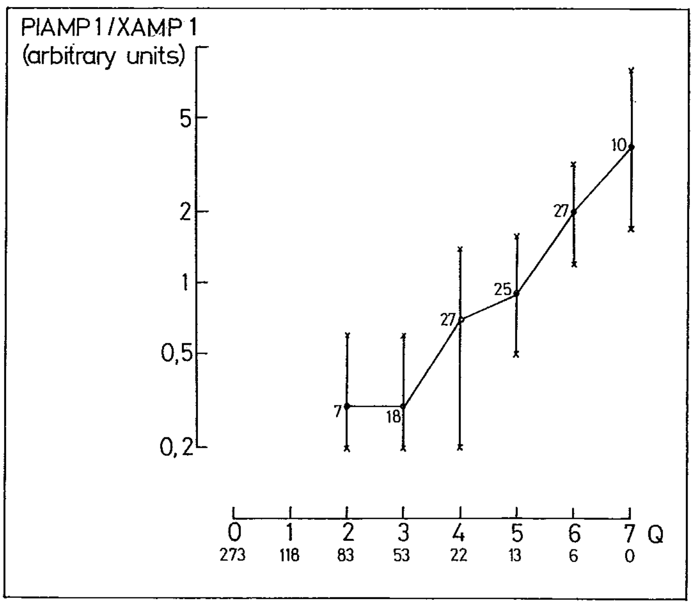

Fig. 12. Changes in the quantity PIAMP 1/XAMP 1 as a function of the Sodankylä Q-index.

7. *Summary of results*

The observational results presented and reviewed in this study are summarized as follows:

1. At the Sodankylä latitude ($L = 5.2$) the direct electron precipitation associated with the acceleration mechanism appears when $Q \geq 4$ locally. During lower Q-values mainly the drift precipitation is observed.
2. The amplitude of x-ray fast pulsations in the period range of 5—30 second increases toward the morning hours. It is not depending in any pronounced way on the precipitation intensity, except perhaps for some short periods around midnight.
3. The most prominent x-ray pulsations occur to the south from the main auroral activity, *i.e.* they occur during low Q-values.
4. In general, pulsation characteristics are similar in the auroral and x-ray energy ranges. It seems that precipitation pulsations occur mainly in electron energies less than 50 keV.
5. The *Pi* 1 amplitude increases toward the morning hours except for a minimum at around 08 LT. It seems to be related to precipitation intensity around midnight and in the morning hours for the periods of high and low local magnetic activity, respectively.
6. The most prominent *Pi* activity around midnight is associated with a high electrojet intensity ($Q \geq 4$). The *Pi* amplitude observed during low local magnetic activity ($Q < 4$) increases toward the morning sector.
7. Although we must admit that particle and field variations are at least timewise causally coupled, the precipitation pulsation amplitude is not very strongly dependent on the micropulsation amplitude.

8. *Discussion*

A great deal of the magnetospheric substorm energy is manifested by the auroral-zone electron precipitation events. It is concentrated around the midnight sector from where energy is partly transported towards the noon sector, *e.g.* as a result of the drift in the geomagnetic field. Due to this dominant role of electron precipitation events many other auroral-zone phenomena should be considered as secondary effects controlled by magnetospheric electrons.

On the basis of the present analysis summarized above it has to be concluded that at least two basically different mechanisms generate the auroral-zone pulsation characteristics. One is associated with the acceleration of auroral-zone electrons occurring close to the auroral electrojet, the other one is governed by the population of drifting electrons in the magnetosphere. In this picture, the former mechanism operates mainly in the midnight sector of the auroral zone whereas the latter one is most effective during morning hours.

The development of the *Pi* 1 micropulsation activity in the midnight sector is in a very prominent way controlled by the development of the substorm. On the other hand, precipitation pulsations appear only timewise in a close vicinity of the auroral electrojet (see *e.g.* [21, 22]). Thus it seems that both the field and particle pulsation characteristics are directly related to the fundamental nature of the acceleration and precipitation mechanisms in the midnight sector. Consequently, the theories for *Pi* 1 micropulsations like those proposed by NISHIDA [27] and CAMPBELL [9] might be discussed here. Precipitation pulsations may be taken as an indication of the changes in the acceleration mechanism [6, 32, 37].

The main body of the *Pi* 1 activity during the recovery phase of the substorm and in the morning sector of the auroral zone is apparently related to the drift of low-energy magnetospheric electrons. This is indicated by the fact that before the minimum appearing close to the morning maximum of hard precipitation events a close correlation between the *Pi* amplitude and precipitation activity has been observed for low Q-values. Due to the scattering processes low-energy electrons will be effectively removed by the late morning hours [1]. Absorption effects from the high ionization produced by the hard electron precipitation may contribute also somewhat to the decrease of the *Pi* 1 amplitude around 08 LT. In any case, generation mechanisms of *Pi*'s like that proposed by CORONITI and KENNEL [12] should be considered as possible explanations for *Pi* activity in the morning sector of the auroral zone.

It is quite evident that particle pulsations in the morning sector are generated locally, as an increase in x-ray pulsation amplitude as a function of local time has been observed. Otherwise, the energy-dependent dispersion during the drift should smear out the intensity variations.

It is popular to relate the precipitation pulsations to a modulation effect of micropulsations. It has been shown by CORONITI and KENNEL

[11] that in the frame of the whistler turbulence theory for the electron precipitation events the whistler growth rate should be modulated by a low-frequency micropulsation. If the micropulsation period is much shorter than the electron lifetime then in the case of the weak diffusion rate an exponential increase in precipitation pulsation amplitude may occur. In the case of the strong diffusion rate no such a relation should be expected. On the basis of these considerations it seems again justified that in the midnight sector where strong diffusion occurs and where we have found a significant correlation between particle and field pulsation amplitudes during high Q-values the pulsation characteristics are manifestations of primary acceleration and precipitation mechanisms in the source region of the substorm activity. On the other hand, weak pitch angle scattering of the electrons by whistler mode waves seems to dominate in the morning sector [5] and high-amplitude particle pulsations should appear. However, it is the conclusion of the present analysis that micropulsation and particle pulsation amplitudes are not coupled in such a strict way as discussed theoretically by CORONITI and KENNEL [11]. Although CORONITI and KENNEL [11] have thrown some doubt on a comparison with observations such as made here it seems that modulation effects on electron fluxes by micropulsations do not depend very much on micropulsation intensity.

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