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SOLAR CYCLE CHANGE OF Pc1 WAVES OBSERVED BY AN EQUATORIAL SATELLITE AND ON THE GROUND

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ABSTRACT

Ion cyclotron wave (Pc1 pulsation) activity on the ground has been found to depend strongly on solar activity: Pc1 pulsations occur considerably more often during solar minimum than solar maximum conditions. We have now studied Pc1 wave activity observed by the AMPTE/CCE satellite close to the equatorial source region of these waves, and simultaneously on the ground at Sodankylä, Finland, during two periods of contrasting solar activity levels: August 1985 - May 1986 (with average daily sunspot number of 13.9) and May 1988 - January 1989 (118.2). The total occurrence rate of waves in space decreased by a factor 1.6 from low to high sunspot times, in good agreement with a simultaneous decrease observed for high-latitude unstructured Pc1's on ground. The structured Pc1's (classical pearls) suffer a greater depletion in high sunspot times. The data suggests that the long-term variation of high-latitude Pc1's may entirely be due to a change in wave generation. Another, holistic view on wave appearance in a given flux tube with several factors affecting the observed changes is also possible. Ionospheric ducting does not seem to be a significant factor in regulating long-term activity of high-latitude Pc1's. The data also suggests a nonlinear dependence between Pc1 activity and solar activity as measured by sunspot numbers.

INTRODUCTION

Near-Earth space plasmas, in particular the ionosphere and magnetosphere, are influenced by the changing solar activity. As a response to this influence, some near-Earth plasma phenomena experience large modifications over the solar 11-year cycle. Long-term observations are able to give the overall scale of such natural variations. They may also help in better understanding the origin and causal relations between these phenomena, as well as the related microphysics in the varying plasma conditions provided by the changing solar activity.

While studies on the long-term development of longer period waves are relatively few, Pc1 pulsations have been studied for a long time. This is mainly due to fact that Pc1 pulsations are easily identifiable and the relevant frequency range can be easily covered. Furthermore, the observed long-term changes are dramatic. The annual amount of Pc1 pulsations at low geomagnetic latitudes is in approximate inverse relation to the annual sunspot number /1,2/. The same relation is observed both at mid- /3/ and high latitudes /4/ in observations extending over several complete solar cycles. This relation was verified /5/ to be separately valid for the two most common types of Pc1 pulsations: structured Pc1's (periodic emissions) and unstructured Pc1's. Despite this roughly similar pattern, some differences have also been observed in the solar cycle variation of Pc1's between low and high latitudes /4/ as well as between the two Pc1 types detected at high latitudes /5/.

Until now, the long-term evolution of Pc1 pulsations has been studied only using ground-based observations which are always affected by ionospheric screening. Using ground-based data only, it is impossible to distinguish between the different magnetospheric and ionospheric mechanisms that may contribute to the solar cycle variation of Pc1 waves. Therefore, it is highly desirable to make long-term wave observations on a satellite, close to the equatorial source region of the waves, and to compare them with the simultaneous observations on the ground.

OBSERVATIONS

We studied the Pc1's observed close to the equator by the AMPTE/CCE satellite and simultaneously on ground by the Sodankylä station (L=5.1). The study period covered one nearly complete CCE apogee rotation period both in low solar activity time (from day 214/1985 to day 151/1986) and in high solar activity time (from day 123/1988 to day 007/1989). The former period included some of the most quiet sunspot months with an average daily sunspot number of 13.9. The latter period, extending until the end of the CCE mission, took place in the late ascending phase of the solar cycle 22, only a few months before the sunspot maximum, and had an average sunspot number of 118.2. Accordingly, we are able to compare low and high solar activity times whose sunspot numbers differ by nearly one order of magnitude.

The CCE observations in the low (high) sunspot times covered 5031 (4712) hours of observations. The total time of Pc1 wave activity, determined as described in /6/, during these periods was 271 (157) hours. Thus CCE observed Pc1 activity during 5.39% of the low sunspot time but only 3.34% of the high sunspot time, implying a low/high ratio of 1.61. The estimated error in this ratio is about 0.08 (1σ).

The Pc1 occurrence rate distributions in MLT are given in Figure 1 for five ranges of L. The MLT-L occurrence patterns for the two periods are quite similar to each other, and to those detected earlier /6/.

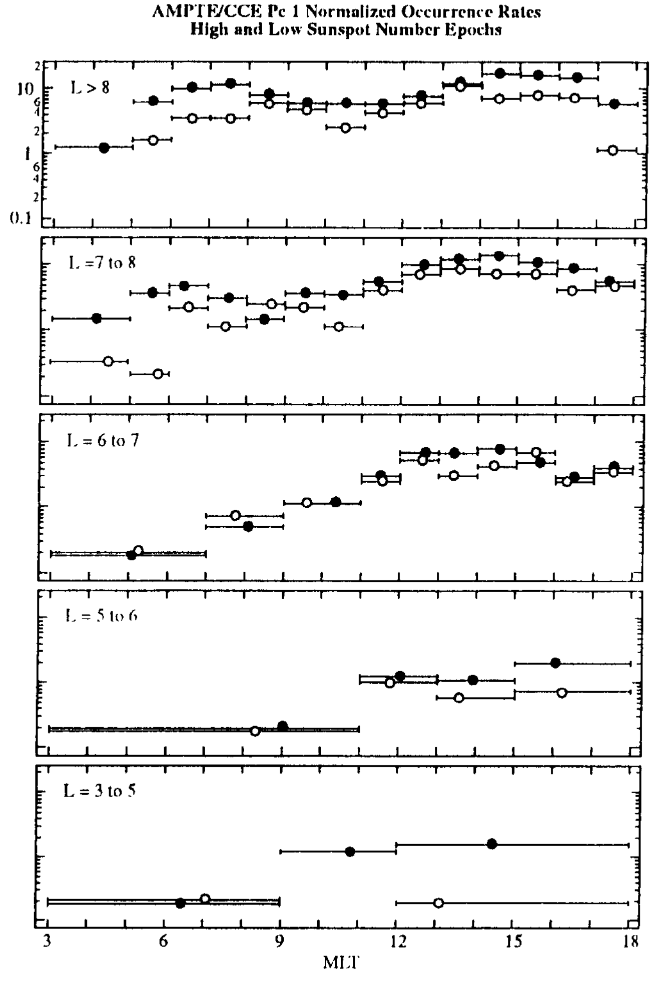

Fig. 1. The MLT distribution (from 03 to 18) of normalized Pc1 activity observed by the AMPTE/CCE satellite for 5 ranges of L-values. The black (open) dots correspond to the low (high) sunspot period.

In both low and high sunspot times, the Pc1 occurrence increases with L and has its diurnal maximum in the postnoon sector. Furthermore, some other properties (absolute and normalized frequency, ellipticity and power) of CCE Pc1 waves were studied and compared between the two periods, but no statistically significant difference was found in the overall ensemble averages.

Simultaneously, ground-based Pc1 activity was registered at Sodankylä. We divided ground-based Pc1's into three groups according to their morphological structure, as explained in /5/. The dominant forms of Pc1's at high latitudes are the structured and unstructured waves which together formed 93% (89%) of the total Pc1 activity in the low (high) sunspot times. Structured (unstructured) Pc1's were detected during 8.29% (5.30%) of the low sunspot time and 3.59% (3.49%) of the high sunspot time. Accordingly, the low/high ratios for the two main Pc1 types were quite different (2.31 for structured and 1.52 for unstructured), the structured Pc1's suffering a larger depletion during high solar activity. This confirms our earlier observation /5/ of such a difference between the two Pc1 types. The overall low/high Pc1 activity ratio was 1.83. The diurnal distributions for the two main Pc1 types in the two activity periods are depicted in Figure 2.

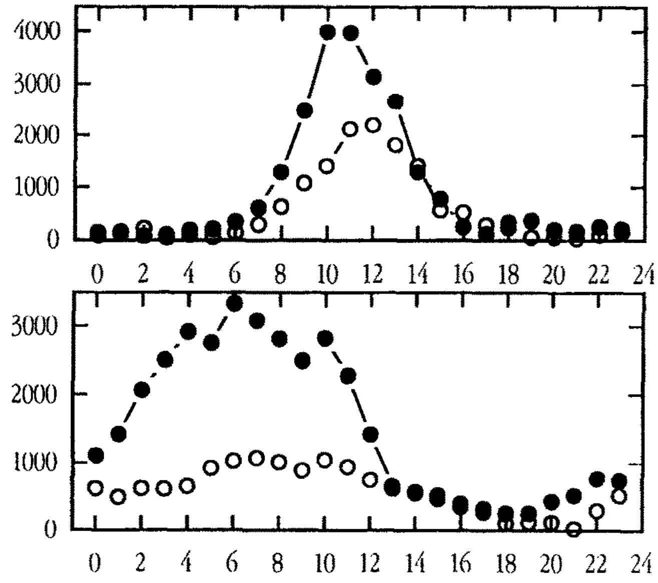

Fig. 2. The diurnal distribution of the unstructured (upper panel) and structured (lower panel) Pc1 waves observed at Sodankylä (L=5.2; MLT≈UT+2.5h). The black (open) dots correspond to the low (high) sunspot period.

We have also studied the occurrence of Pc1 waves observed during AMPTE/CCE passes over Finland in the same two intervals of low and high solar activity. The CCE was resticted to be within 1h MLT of Sodankylä and between L=3 and L=7. Altogether, 71 (74) such CCE-Sodankylä conjunctions occurred during the low (high) sunspot time. The "coincidence" statistics of Pc1 waves during these conjunction events are given in the Table separately for the two contrasting solar activity periods.

The coincidence results show that the wave activity at CCE is very often observed at Sodankylä as well. Out of the 23 conjunctions with CCE wave activity, 20 are observed on the ground. Only 1 (2) event is missed by Sodankylä during low (high) solar activity period. On the other hand, Sodankylä observes a large number of events not detected by CCE. The ratio of those Sodankylä events not seen on CCE over those seen by CCE is 1.25 (1.5) for the low (high) sunspot time. This is in accordance with the above mentioned fact that the overall Pc1 occurrence rates are higher at Sodankylä than on CCE.

TABLE Coincidence statistics of Pc1 events observed simultaneously at Sodankylä and CCE in close conjunction (L=3-7, ΔMLT=1) for low (left) and high (right) sunspot period. Both the number of events and the corresponding percentages (in parenthesis) are given.

Low sunspot number time

		Sod Pc1 Yes	Sod Pc1 No
CCE Pc1	Yes	12 (16.9 %)	1 (1.4 %)
	No	15 (21.1 %)	43 (60.6 %)

High sunspot number time

		Sod Pc1 Yes	Sod Pc1 No
CCE Pc1	Yes	8 (10.8 %)	2 (2.7 %)
	No	12 (16.2 %)	52 (70.3 %)

DISCUSSION AND CONCLUSIONS

In agreement with previous studies, the diurnal distributions of the two ground-based Pc1 types (Fig. 2) are very different, reflecting the different source of these pulsations. While the structured Pc1's are known to be connected with plasmapause, the source of unstructured Pc1's is at higher latitudes. The diurnal distribution of each of the two Pc1 types remains roughly similar during low and high sunspot times, implying that the two populations are indeed separate over the solar cycle. (Some small changes do appear over the solar cycle as noted earlier /5/).

The high-latitude source and the diurnal distribution of the unstructured pulsations are in accordance with the properties of CCE Pc1 events (high-L maximum, post-noon MLT maximum; see Fig. 1). Thus it is natural to identify the bulk of the CCE events with unstructured Pc1's on ground. The CCE events and the unstructured Pc1's on the ground also suffer very similar depletion over the solar cycle, the low/high ratio being 1.61 and 1.52 respectively, while the structured Pc1's are depleted considerably more during the high sunspot time.

The CCE observations clearly demonstrate that the Pc1 activity is depleted at the equatorial source region in high sunspot times. Furthermore, the similar depletion ratios at the equator and on ground suggest that the strong solar cycle variation of unstructured Pc1 waves over the whole cycle is indeed related to a corresponding change at the wave source region. This new observation is very useful when trying to clarify the main effects causing the dramatic solar cycle variation of Pc1 waves.

As mentioned above, Sodankylä observes a large fraction of events not detected by CCE. Many of these waves probably come to Sodankylä by ducting in the ionospheric waveguide from source field lines at higher L-shells than Sodankylä. The similar depletion of CCE events and unstructured Pc1's suggests that no significant change in the ionospheric ducting conditions occurred over the solar cycle and that, accordingly, changing ducting conditions can not be the main factor causing the solar cycle change of high-latitude Pc1 waves. This conlusion is also supported by the fact that the fraction of those Sodankylä events not seen on CCE was not smaller (in fact slightly higher; see Table) in high sunspot times compared to low sunspot times. These are most likely waves generated at field lines outside CCE (e.g. at higher L-shells than the L=3-7 range) and are ducted to Sodankylä. (However, since the CCE ensemble does not represent structured Pc1's it is not clear whether a similar conclusion appies for them. Thus the changing ducting conditions may still be a significant factor for the long-term appearance of structured Pc1's).

In simplest terms, the results can be interpreted to imply that wave generation in the equatorial source region (at high L-shells) changes with the solar cycle in response to solar cycle induced changes in the local plasma parameters important for ion cyclotron wave growth (energetic proton temperature, density, temperature anisotropy, plasma density and composition etc.). This variation in wave generation is then reflected on the ground as a corresponding change of unstructured Pc1 occurrence, with no further major modifications by other possible effects occurring during wave propagation from the equator to the ground. In this "external" interpretation, no feedback mechanism from the ionosphere to the equatorial region is needed.

A more "holistic" interpretation of the results is also possible. It may be that there is an efficient feedback mechanism in which waves are reflected from the ionosphere and propagate back to the equator where they are re-amplified. Wave activity as recorded both in space and on the ground would therefore be affected both by the propagation and reflection characteristics of the flux tube in addition to wave growth rate. This interpretation is motivated by the classical idea of Pc1 pearls as wave packets bouncing between the two hemispheres (although, by definition, pearl structure itself is not relevant for unstructured pulsations). Each flux tube is regarded as an entity whose wave activity is controlled as much by the evolution of wave propagation and ionospheric interaction as by the source region growth rate. Once the overall conditions for wave growth in a given flux tube are met, the waves are observed both at the equator and on the ground.

We also note that the overall depletion of Pc1 wave activity observed here was quite small (less than a factor of 2), although we compared the minimum and pre-maximum sunspot phases with sunspot number ratio as high as 8.5. The variation of ground Pc1 activity between actual sunspot minimum and maximum times is much greater: a depletion by a factor of 7.1 for a sunspot ratio of 9.2 was found /5/. The relatively low depletion found between the periods examined in this study implies a nonlinear dependence of Pc1 occurrence on sunspot activity. There may be a threshold effect (wave activity is sizably depleted only beyond some limit value) or a time lag, if for example the factors controlling Pc1 occurrence have, in net effect, a different solar cycle dependence than sunspots with a maximum after the sunspot maximum.

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