Coherent multiple Pc1 pulsation bands: possible evidence for the ionospheric Alfvén resonator

F. Z. Feygin[1], A. K. Nekrasov[1], K. Mursula[2], J. Kangas[2], T. Pikkarainen[2]

[1] Institute of the Physics of the Earth, Moscow, USSR
[2] Department of Physics, University of Oulu, Finland

Received: 12 May 1993 / Revised: 2 December 1993 / Accepted: 3 January 1994

Abstract. A fair fraction of Pc1 pulsation events observed on the ground includes more than one simultaneous pulsation band. In most such multiband events the bands display different characteristics and, therefore, come from different source regions via horizontal ducting in the ionosphere. However, in this report we identify a new "coherent" subclass of multiband Pc1 events where the pearls of the simultaneous bands have the same group velocities (repetition rates) as well as dispersion and other properties, thus implying that the bands are produced by the same source. Studying one example of such a coherent multiband event in more detail, we argue that these events defy an explanation in terms of band splitting by magnetospheric heavy ions because the observed frequency gap between the bands is smaller than would result in such a case. We interpret these events to be due to the frequency dependence of the ionospheric reflection coefficient of Alfvén waves. An oscillatory frequency dependence of the coefficient is a natural consequence of the idea that the ionosphere acts as a resonator for Alfvén waves. We also discuss other predictions of this interpretation.

1 Introduction

The Pc1 micropulsations were detected in the 1930s (Harang, 1936, Sucksdorff, 1936), and have since then been investigated both theoretically and experimentally (for early reviews, see Saito, 1969; Troitskaya and Gul'elmi, 1969; Jacobs, 1970). Pc1 pulsations have further been classified into various subgroups (Fukunishi *et al.*, 1981) according to the morphology of observed dynamic spectra. Dividing the Pc1s roughly into two groups, structured and unstructured Pc1s, it has been found that the structured pulsations (also called periodic or pearl pulsations) are the main Pc1 type at low and midlatitudes, while at high latitudes unstructured pulsations dominate. Ground-based observations have also been used to study the long-term (solar cycle) behaviour of Pc1 pulsations at both midlatitudes (Matveyeva, 1987) and at high latitudes (Mursula *et al.*, 1991). Pc1 properties have also been studied at cusp/cleft latitudes (Sato and Saemundsson, 1990; Morris and Cole, 1991). Magnetospheric ion cyclotron waves have been studied by satellite instruments recently by the midaltitude polar-orbiting Viking satellite (Erlandson *et al.*, 1990) and the near-equatorial AMPTE/CCE satellite (Anderson *et al.*, 1992a, b). On the theoretical side the effects of the inhomogeneous magnetic field on the generation (Kurchasov *et al.*, 1987; Nekrasov, 1987) and propagation (Nekrasov *et al.*, 1991) of ion cyclotron waves have been studied. Also, the red-violet asymmetry in the occasional appearance of the so-called pearl satellites in periodic Pc1 pulsations has been observed (Feygin *et al.*, 1985) and interpreted in terms of the decay instability of Alfvén waves (Feygin, 1987).

In a most common Pc1 event observed on the ground, whether structured or unstructured, the wave power of the dynamic spectrum is restricted to a single narrow frequency band. However, in addition to these dominant single-band Pc1 events one observes fairly frequently events whose dynamic spectra show two or more simultaneous but clearly separate Pc1 bands. We call these events multiband Pc1 events. Multiband Pc1 events can be produced, e.g. by ducting of waves in the ionospheric waveguide from multiple sources, or by the spectral splitting induced by magnetospheric heavy ions, mainly the He^+ and O^+ ions (see e.g. Young *et al.*, 1981; Kozyra *et al.*, 1984). According to the latter mechanism, a forbidden region is formed above each heavy ion gyrofrequency, thus splitting the spectrum into 2–3 pass bands and the intervening stop bands. Observations of such splitting have been conducted by the GEOS-1/2 satellites (Young *et al.*, 1981).

However, spectral studies of ground-based Pc1 pulsations have mainly confined their analysis to single-band Pc1 events with little attention having been paid so far to a detailed analysis of multiband events. In this paper we discuss multiband Pc1 events and show that such events may be able to shed new light on the physics of Pc1 pulsations. In particular, we introduce a special "coherent" subclass of structured multiband events and argue that such coherent multiband events give evidence for a strong modification of Pc1 waves caused by a frequency-dependent ionospheric reflection coefficient of Alfvén waves.

2 Multiband Pc1 events

As is well known, Pc1 waves can travel horizontally in the ionospheric waveguide (Greifinger and Greifinger, 1968) away from the footpoint of the field line along which they propagate from the magnetospheric source region to the ionosphere. Therefore, ground-based observers can register waves that have their footpoint not only close to the observation site but quite far from there. Occasionally, if simultaneous Pc1 activity exists in more than one region, one may thus observe several simultaneous Pc1 waves on ground.

The simultaneous waves coming from sources at different latitudes have, in general, different frequencies and may thus form a multiband Pc1 event with two or more separate bands. Furthermore, the different bands of structured multiband events generally have different wave packet group delay (pearl repetition) times and other pearl characteristics because the waves have propagated in the magnetosphere along field lines of unequal lengths and passed through different plasma regions.

Based on an extensive set of ground-based multiband Pc1 events from both midlatitudes (Sogra, Kerguelen, Oulu and Nurmijärvi stations) and high latitudes (Sodankylä station), we could verify that most multiband events indeed show clear differences between the bands, indicating that they have different origins. Figure 1 depicts a typical multiband event of two simultaneous structured Pc1 bands with clearly different pearl structures. The group delay time of pearls and the dispersion of the individual pearls in the two bands are seen to be different. In many multiband events, particularly at high latitudes, one observes both an unstructured and a structured Pc1 band, which clearly must have different origins. However, in addition to this dominant type of multiband events showing mutual differences between the bands, there are other, although quite rare, structured multiband events where the different bands seem to have exactly the same properties (except for frequency). In these events, the simultaneous structured Pc1 bands have the same group delay times, dispersion characteristics and other properties of the pearl structure. Also, the individual pearls tend to appear simultaneously in the different bands. Since the various bands in these events seem to be formed by a single mechanism we call them coherent multiband events. It is clear that such similarity and coherence cannot be understood in terms of the above-mentioned ducting of waves from different regions in the ionospheric waveguide.

Figure 2 shows an example of a coherent multiband event with three simultaneous Pc1 bands during some 15 min around 0330 UT. The preceding and succeeding Pc1 activity shows long two-band and occasional fainter three-band structures. In total, this Pc1 activity, which was earlier studied by Baransky *et al.* (1981), lasted for several hours. The midfrequencies of the three bands at around 0330 UT are roughly at 1.2 Hz, 1.6 Hz and 1.9 Hz. The common group delay time between successive pearls is about 77 s. Using the method presented by Al'pert and Fligel (1977) and Kurchashov *et al.* (1989), one can determine the footpoint of the source of this event to be at

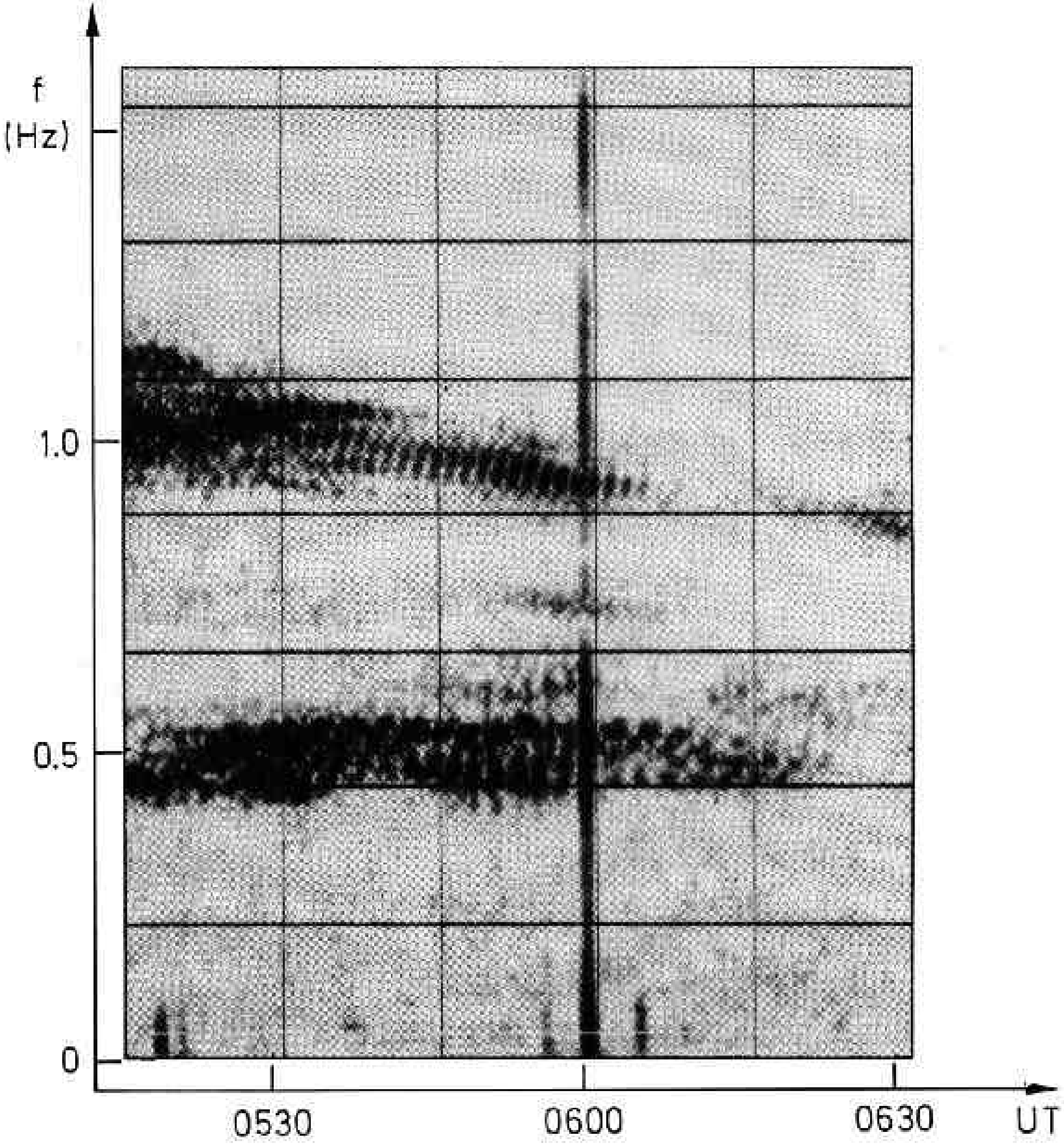

Fig. 1. The sonogram of pulsations observed at Oulu (65.1° GGlat, 25.5° GGlong, 61.8° CGMlat, 107° CGMlong) on April 2, 1975 (0500–0630 UT). The two simultaneous bands of structured pulsations have different group repetition times and dispersions

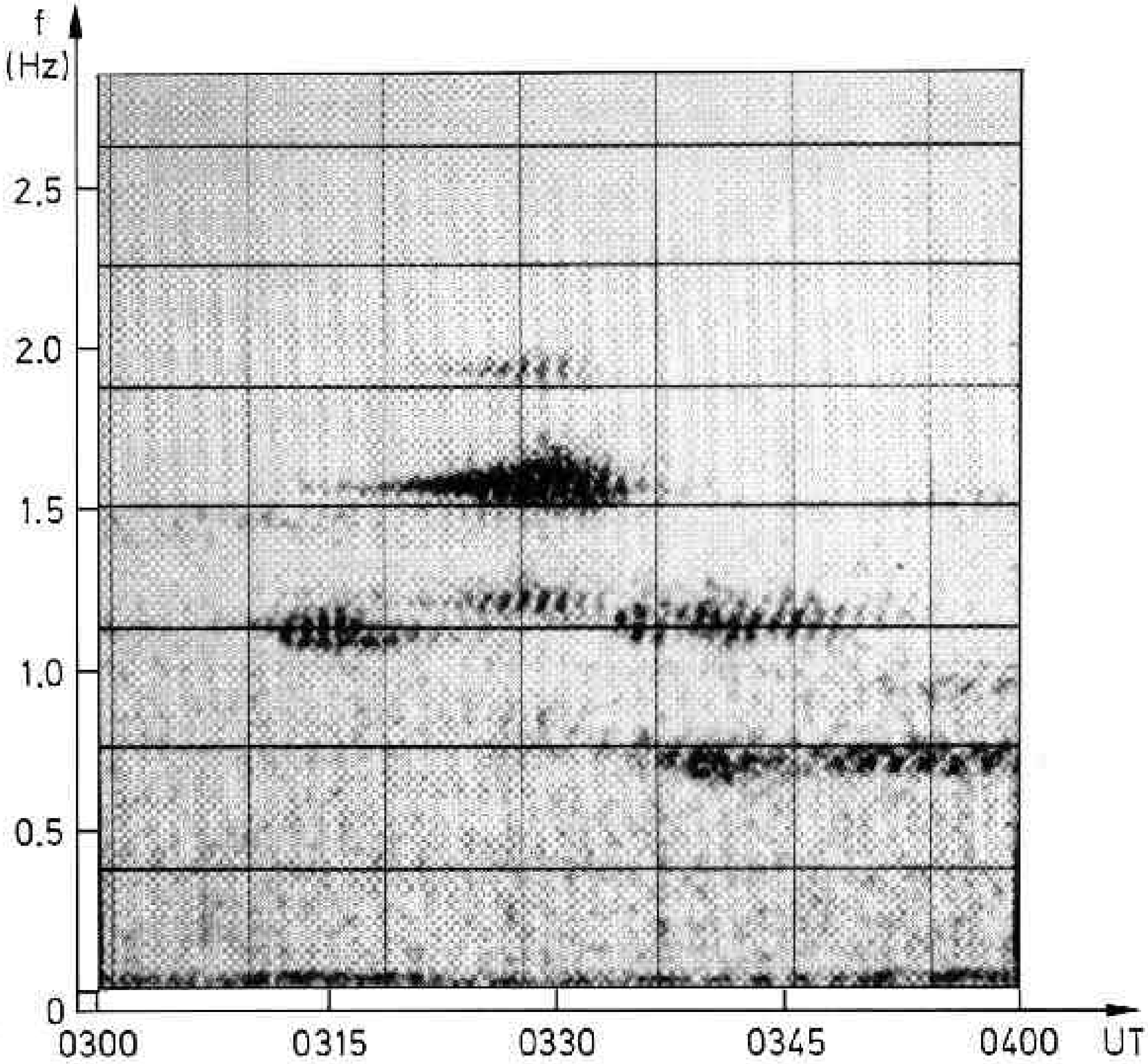

Fig. 2. The sonogram of pulsations observed at Nurmijärvi (60.5° GGlat, 24.7° GGlong, 57.0° CGMlat, 103° CGMlong) on December 7, 1977 (0230–0400 UT) showing three coherent simultaneous bands of Pc1 pearl pulsations for about 15 min at around 0330 UT

$L \simeq 3.5$–4. Thus, the source was quite close to the latitude of the Nurmijärvi Observatory ($L = 3.4$). Although all three bands are quite narrow, the similar dispersion slope and the simultaneous occurrence of pearls in the three bands are clearly seen for some six pearls of this event.

3 Interpretation of coherent multiband events

The appearance of coherent multiple Pc1 bands can be explained naturally by the frequency dependence of the reflection coefficient of Alfvén waves from the ionosphere. It has been shown (Polyakov and Rapoport, 1981; Prikner and Vagner, 1988; Rudenko, 1990) that the Earth's ionospheric layer, which has a thickness of about 1500 km, forms a resonator for Alfvén waves in the Pc1 frequency range. For waves travelling from the magnetosphere to the Earth the Alfvén resonator is a reflective layer. The reflection coefficient from this layer is strongly dependent on the frequency of the incoming wave, showing minima and maxima in the Pc1 frequency range. This dependence has the most pronounced form for the night ionosphere (Prikner and Vagner, 1988; Rudenko, 1990). One may note in passing that most structured events are observed in the post-midnight to early morning sector (see e.g. Saito, 1969). According to Prikner and Vagner (1988) and Rudenko (1990), the minima of the reflection coefficient correspond to the eigenmodes of the ionospheric Alfvén resonator. The frequency difference between two consecutive maxima of the reflection coefficient depends on the latitude and ranges between 0.3 and 0.8 Hz (Rudenko, 1990). This is in agreement with Fig. 2 where the frequency gaps between the successive bands are 0.3–0.4 Hz.

The Alfvén wave, amplified at a fairly wide frequency range in the magnetospheric source region and travelling towards the Earth, is reflected from the ionosphere at frequencies that correspond to the maxima of the reflection coefficient. The reflected waves will be amplified again in the magnetosphere and return back after reflection from the conjugate ionosphere. This process is repeated many times. As a result, the wave amplitude achieves a value large enough to penetrate through the ionosphere, and the wave is observed on the ground. The ratio of wave amplitudes measured on the ground and on board a satellite is of the order of 0.01–0.05 (Prikner and Fligel, 1991). This is in agreement with the view that pulsations that are observed on the ground indeed suffer sizable reflection from the ionosphere. (Of course, wave power can also partially be lost in ducting and dissipation.) In effect, the ionosphere acts as a pass-band filter for the Pc1 waves and determines, together with the magnetospheric source, the frequencies of the waves that can grow large.

The reflection of the wave spectrum from the ionosphere, the ensuing increase of the wave in the magnetosphere, and the wave's partial penetration to the ground form the standard picture for the formation of structured Pc1 pulsations. Because of the oscillative structure of the ionospheric reflection coefficient, more than one Pc1 band can occasionally be formed in favourable conditions. These are then seen as coherent multiband events on the ground.

4 Discussion

Another possible mechanism to produce coherent multiband Pc1 events might be the influence of magnetospheric heavy ions (most importantly, He^+ and O^+) on the generation and propagation of Alfvén waves. As mentioned in the Introduction, it is well known (Young *et al.*, 1981; Kozyra *et al.*, 1984; Nekrasov, 1987; Nekrasov *et al.*, 1991) that the presence of heavy ions in the magnetosphere may result in the formation of gaps in the pulsation spectrum above the gyrofrequencies of the heavy ions. Also, the wave growth rate in such a multi-ion plasma is divided into separate frequency ranges, each located below the respective heavy ion gyrofrequency but above the cutoff frequency of the next heavy ion (Kozyra *et al.*, 1984).

If the heavy ions were to form all the observed three simultaneous bands of the event of Fig. 2, the lowest band should have a frequency below the O^+ gyrofrequency and the highest band above the He^+ gyrofrequency. In this case the values of the equatorial gyrofrequencies of O^+ and He^+ at the approximate wave source shell between $L = 3.5$ and $L = 4$ vary for He^+ from $f_{He^+} = 2.8$ Hz to $f_{He^+} = 2.0$ Hz, and for O^+ from $f_{O^+} = 0.7$ Hz to $f_{O^+} = 0.5$ Hz. Accordingly, the difference between the He^+ and O^+ gyrofrequencies is about 1.5–2.0 Hz. This is clearly larger than the observed difference of about 0.7 Hz, not smaller, as it should be if heavy ions were to form the three bands. Therefore, we conclude that magnetospheric heavy ions cannot be the cause of coherent multiband Pc1 events.

Furthermore, in a more detailed comparison, it would be difficult to find plasma conditions where the frequency difference between the oxygen and helium growth regions would be small enough to be of the observed value of 0.3–0.4 Hz. On the other hand, the frequency range between the above calculated O^+ and He^+ gyrofrequencies corresponds very well to the observed frequency range of the three bands of Fig. 2. Therefore, it is probable that all the three observed bands are amplified in the same wave growth range between O^+ cutoff frequency and He^+ gyrofrequency, and not from two or three different ranges.

The small number of coherent multiband events among all multiband events may be explained by the many conditions that have to be fulfilled in order to produce such events. First of all, the magnetospheric source must amplify waves at a rather large range of frequencies since, as discussed above, the different bands probably originate from the same growth rate range. Secondly, this range must be appropriately located for the frequencies corresponding to the maxima of the ionospheric reflection coefficient. Moreover, the maxima of the two ionospheric ends of the wave field line must sufficiently overlap in order to maintain sufficient wave growth and coherence. (Accordingly, conjugate stations should simultaneously observe coherent multiband events with roughly similar properties. Unfortunately, no stations exist conjugate to the Finnish search coil magnetometers to verify this.)

Based on observations made at the different Finnish stations extending from $L \simeq 3$ to $L \simeq 6$, coherent structured multiband events were detected at mid- rather than high latitudes. This may be due to the dependence of the ionospheric reflection coefficient on the latitude. Due to the larger angle of incidence, the resonance structure is more pronounced at midlatitudes (Prikner and Vagner, 1988). For example, there are more spikes in the reflection coefficient (3–4 in the Pc1 frequency range) at midlatitudes than at high latitudes (1–2).

The proposed interpretation suggests that the ionosphere has, in addition to its effect on the horizontal propagation of the waves, an active role in selecting which frequencies are eventually amplified enough to produce structured Pc1 events on the ground. This selection is not restricted to the special case of coherent multiband events, but affects all ion cyclotron wave activity. However, the former may, as discussed in this paper, be useful in demonstrating the proposed mechanism to be operative.

We would also like to note that this interpretation predicts that the annual occurrence of all (not only multiband) structured Pc1s tends, when other affecting factors are the same, to maximize during equinoxes when the ionospheres in the two hemispheres at both ends of the wave field line are as similar as possible, thus amplifying the same frequencies. The differences in the frequencies of the reflection maxima between summer and winter ionospheres, on the other hand, make it statistically more difficult for waves to be amplified. Also, this may lead to a smaller band width of Pc1 pulsations in summer and winter. While there are no experimental studies on the latter effect, the annual distribution of structured Pc1s at midlatitudes indeed seems to maximize during equinoxes (Fraser-Smith, 1970). (So far, such equinoctial preference has been connected with similar biannual behaviour of the general geomagnetic activity.)

5 Conclusion

In this paper we have discussed multiband Pc1 events observed on the ground, i.e. events that include two or more simultaneous Pc1 bands at different frequencies. While the different bands of most such events seemingly come from different magnetospheric sources via horizontal ducting of waves, we presented and discussed a small "coherent" subclass of structured multiband events whose properties cannot easily be explained by horizontal ducting or other well-known effects, such as band splitting by magnetospheric heavy ions. Discussing one such event as an example, we argued that the only viable explanation for the appearance of these events is the frequency dependence of the reflection coefficient of Alfvén waves from the ionosphere. Such a dependence is a natural consequence of the resonator properties of the ionosphere for these waves.

Acknowledgements. We wish to thank Victor Trakhtengerts and Tilmann Bösinger for interesting discussions. K. M. acknowledges the support of the Academy of Finland. This work was also supported by the Committee for Scientific Cooperation between Finland and Russia.

The Editor-in-Chief, S. W. H. Cowley thanks Dr. Y. Hu and Dr. R. Erlandson for their help in refereeing this paper.

References

Al'pert Y., and D. S. Fligel, The locating of hydromagnetic whistler sources and determination of their generating proton spectra, *Planet. Space Sci.*, **25**, 487–497, 1977.

Anderson, B. J., R. E. Erlandson, and L. J. Zanetti, A statistical study of Pc1-2 magnetic pulsations in the equatorial magnetosphere. 1. Equatorial occurrence distributions, *J. Geophys. Res.*, **97**, 3075–3088, 1992a.

Anderson, B. J., R. E. Erlandson, and L. J. Zanetti, A statistical study of Pc1-2 magnetic pulsations in the equatorial magnetosphere. 2. Wave properties, *J. Geophys. Res.*, **97**, 3089–3101, 1992b.

Baransky, L., Y. Golikov, F. Feygin, I. Harchenko, J. Kangas, and T. Pikkarainen, Role of the plasmasphere and ionosphere in the generation and propagation of pearl pulsations, *J. Atmos. Terr. Phys.*, **43**, 875–881, 1981.

Erlandson, R. E., L. J. Zanetti, T. A. Potemra, L. P. Block, and G. Holmgren, Viking magnetic and electric field observations of Pc1 waves at high latitudes, *J. Geophys. Res.*, **95**, 5941–5955, 1990.

Feygin, F. Z., Nature of the red-violet asymmetry in the production of "pearl" satellites, *Geomagn. Aeron.*, **27**, 908–909, 1987.

Feygin, F. Z., Y. P. Kurchashov, V. A. Troitskaya, and K. Dobesh, Red-violet asymmetry in pearl satellites' birth, *Planet. Space Sci.*, **33**, 271–273, 1985.

Fraser-Smith, A. C., Some statistics on Pc1 geomagnetic micropulsation occurrence at middle latitudes: inverse relation with sunspot cycle and semiannual period, *J. Geophys. Res.*, **75**, 4735–4745, 1970.

Fukunishi, H., T. Toya, K. Koike, M. Kuwashima, and M. Kawamura, Classification of hydromagnetic emissions based on frequency-time spectra, *J. Geophys. Res.*, **86**, 9029–9039, 1981.

Greifinger, C., and P. Greifinger, Theory of hydromagnetic propagation in the ionospheric waveguide, *J. Geophys. Res.*, **73**, 7473–7490, 1968.

Harang, L., Oscillations and vibrations in magnetic records at high-latitude stations, *Terr. Magn. Atmos. Electr.*, **41**, 329–336, 1936.

Jacobs, J. A., *Geomagnetic micropulsations*, Springer Verlag, Berlin-Heidelberg, 1970.

Kozyra, J. U., T. E. Cravens, A. F. Nagy, E. G. Fontheim, and R. S. B. Ong, Effects of energetic heavy ions on electromagnetic ion cyclotron wave generation in the plasmapause region, *J. Geophys. Res.*, **89**, 2217–2233, 1984.

Kurchashov, Y. P., N. V. Petviashvili, O. A. Pokhotelov, and F. Z. Feygin, Cyclotron instability of the magnetospheric plasma in a longitudinally nonuniform magnetic field, *Geomagn. Aeron.*, **27**, 386–391, 1987.

Kurchashov, Y. P., O. A. Pokhotelov, F. Z. Feygin, and K. Dobesh, A method of remote sounding of the magnetosphere plasma according to the characteristics of the Pc1 pulsations for a plasma of finite pressure, *Geomagn. Aeron.*, **29**, 363–367, 1989.

Matveyeva, E. T., Cyclic variation of the activity of Pc1 geomagnetic pulsations, *Geomagn. Aeron.*, **27**, 392–395, 1987.

Morris, R. J., and K. D. Cole, High-latitude day-time Pc1-2 continuous magnetic pulsations. A ground signature of the polar cusp and cleft projection, *Planet. Space Sci.*, **39**, 1473–1491, 1991.

Mursula, K., J. Kangas, T. Pikkarainen, and M. Kivinen, Pc1 micropulsations at a high-latitude station: a study over nearly four solar cycles, *J. Geophys. Res.*, **96**, 17651–17661, 1991.

Nekrasov, A. K., Absorption of Pc1, 2 pulsations by heavy ions in equatorial region of the Earth's magnetosphere, *Geomagn. Aeron.*, **27**, 550–555, 1987.

Nekrasov, A. K., K. Mursula, J. Kangas, T. Pikkarainen, and N. F. Maltseva, Inhomogeneity and nonlinearity effects on stop bands of Alfvénic ion cyclotron waves in multicomponent plasma, *J. Geophys. Res.*, **96**, 1767–1773, 1991.

Polyakov, S. V., and V. O. Rapoport, Ionospheric Alfvén resonator, *Geomagn. Aeron.*, **21**, 610–614, 1981.

Prikner, K., and D. Fligel, Filtration of Pc1 wave packets in the ionosphere. Conjugated experiment GEOS-1 – Husafell and results of numerical modelling, *Stud. Geophys. Geod.*, **35**, 13–32, 1991.

Prikner, K., and V. Vagner, Changes in the reflectivity of the mid-latitude ionosphere with respect to the ULF (Pc1) signal, *Stud. Geophys. Geod.*, **32,** 84–100, 1988.

Rudenko. G. V., Numerical investigation of the Alfvén resonator in the ionosphere, *Radiophys. Quantum Electron.*, **33,** No. 2, 117–124, 1990.

Saito, T., Geomagnetic pulsations, *Space Sci. Rev.*, **10,** 322–412, 1969.

Sato, N., and T. Saemundsson, Unstructured Pc1-2 pulsations observed at geomagnetically conjugate stations in the auroral zones, *J. Geomagn. Geoelectr.*, **42,** 653–662, 1990.

Sucksdorff, E., Occurrences of rapid micropulsations at Sodankylä during 1932 to 1935, *Terr. Magn. Atmos. Electr.*, **41,** 337–344, 1936.

Troitskaya, V. A., and A. V. Gul'elmi, Geomagnetic pulsations and diagnostics of the magnetosphere, *Sov. Phys. Usp.*, **12,** 195–218, 1969.

Young, D. T., S. Perraut, A. Roux, C. de Villedary, R. Gendrin, A. Korth, G. Kremser, and D. Jones, Wave-particle interactions near Ω_{He^+} observed on GEOS 1 and 2. 1. Propagation of ion cyclotron waves in He^+-rich plasma, *J. Geophys. Res.*, **86,** 6755–6772, 1981.