

NONLINEAR ELECTROMAGNETIC ION CYCLOTRON WAVES

F.Z. Feygin^a, N.G. Kleimenova^a, Yu.G. Khabazin^a and K. Prikner^b

^a*Institute of Physics of the Earth, Russian Academy of Sciences, Bolshaya Gruzinskaya 10, 123995 Moscow, Russia, feygin@ifz.ru*

^b*Geophysical Institute, Acad. Sci. Czech Republic, Bocni II/1401, 14131 Praha 4, Sporilov, Czech Republic, kpr@ig.cas.cz*

Abstract

We analyze nonlinear electromagnetic ion cyclotron (NEMIC) waves with the dynamic spectra which have very narrow spectrum width at the beginning of the event and the very broad spectrum width in the processes of development of the event. These (NEMIC) waves due to both the three-wave interaction and the quasilinear interaction EMIC wave with energetic protons.

Introduction

Electromagnetic ion cyclotron (EMIC) waves in the form Pc1 geomagnetic pulsations have been extensively studied in the past (for reviews, see e.g. Guglielmi and Pokhotelov, 1996; Kangas et al., 1998). They are thought to be wave packets propagating along the magnetic field line between conjugate ionospheres (Jacobs and Watanabe, 1964; Obayashi, 1965). Pc1 pulsations are a consequence of gyroresonant interaction EMIC waves with energetic anisotropic protons (Cornwall, 1965; Kennel and Petschek, 1966; Tverskoi, 1971; Feygin and Yakimenko, 1969; Gendrin et al., 1971).

The classic series of "pearl" pulsations have the characteristic slope of the structural elements on the sonograms corresponding to the more faster propagation along the field line of the low frequency waves in comparison with the high frequency ones for a given wave packet (Feygin and Yakimenko, 1970; Gendrin et al., 1971). Typical dynamical spectra of the pearl pulsations have the form of the fan with a decreasing slope of the successive pearl elements (particularly in the end of the series) in a frequency-time coordinate system (a sonogram). However, we revealed new kinds of Pc1 form: successive wave packets without fan structure and pulsations with very broad frequency spectrum, which differ from the dynamic spectra of the classic Pc 1 pearl pulsations.

In this paper we present the new types of Pc1 pulsations which we revealed at the Finnish network during the detailed experimental analysis of Pc1 pulsations and suggest the interpretation of these events.

Observations

In this study the dynamic spectra of structured Pc1 (pearl) pulsations recorded at Finnish stations Oulu (L=4.3) and Sodankylä (L=5.1) have been analyzed.

The most series of classic Pc1 pearl pulsations have the almost the constant central frequency on the sonograms (f_0) with the spectrum width $\Delta f/f_0 \sim 0.1$. We revealed the geomagnetic pulsations in the frequency range of Pc1 which on the sonograms have very narrow the spectrum width at the beginning of the event and the very broad spectrum width reach ($\Delta f/f_0 \sim 1$) in the processes of development of the event. The obtained events can be divided into three kinds and the examples of such events are represented:

- The events with the spectrum width broadening down (to the smaller frequencies),
- the events with symmetrically broadening spectra in relation to the beginning frequency of event,
- the events with the spectrum width broadening up (to the bigger frequencies).

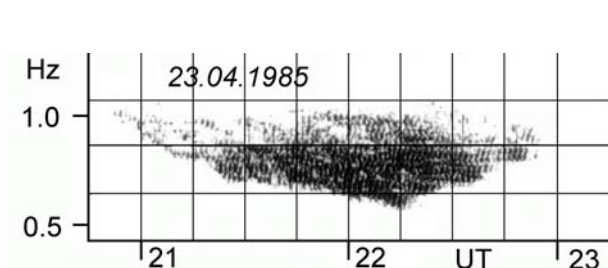


Fig. 1. The event on April 23, 1985 between 20:50 UT and 23:00 UT at Sodankylä Observatory.

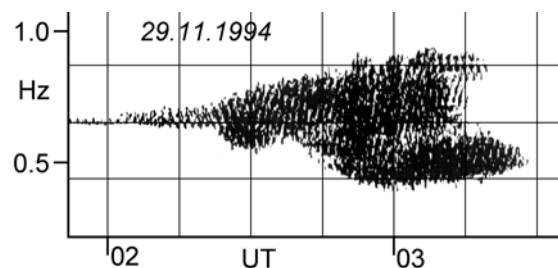


Fig. 2. The event on November 29, 1994 between 02:00 UT and 03:30 UT at Sodankylä Observatory.

Fig.1 illustrates the example of pulsations with frequency spectrum broadening down recorded in Sodankylä on April 24, 1985 at 21 UT. For this event the normalized frequency width in the end of series reaches the value $\Delta f/f_0 \sim$

0.4. Here f_0 is the beginning frequency of the event. This event has the fan structure on the sonogram and the average repetition period $\tau \approx 90$ sec. illustrates the example of pulsations with frequency spectrum broadening down recorded in Sodankyla on April 24, 1985 at 21 UT. For this event the normalized frequency width in the end of series reaches the value $\Delta f/f_0 \sim 0.4$. Here f_0 is the beginning frequency of the event. This event has the fan structure on the sonogram and the average repetition period $\tau \approx 90$ sec.

Fig. 2 shows the example of events with symmetrically broadening spectra in relation to the beginning frequency of the pulsation's series recorded in Sodankyla on November 29, 1994 at 02 UT. The initial frequency of the event is $f_0 = 0.64$ Hz, then the spectrum is symmetrically broadening down and up to $\Delta f/f_0 \sim 0.8$. The event has the fan structure and the average repetition period $\tau \approx 80$ sec.

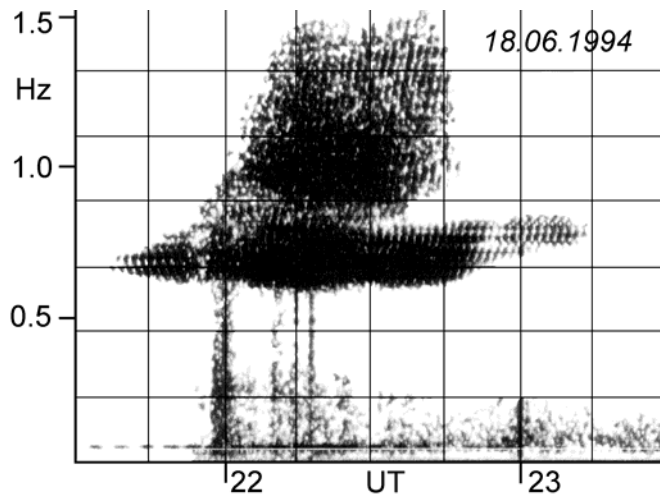


Fig. 3. The event on June 18, 1994 between 21:35 UT and 23:15 UT at Oulu station.

Fig. 3 represents the example of pulsations with the spectrum width broadening up (to the bigger frequencies) recorded in Oulu 18.06.1994 at 21:40 UT. The beginning frequency of the pulsation's series is $f_0 = 0.66$ Hz. The maximum spectral broadening reaches the value $\Delta f/f_0 \sim 1.2$. The average repetition period is $\tau \approx 100$ sec. Characteristic of the event is the absence of fan structure on the dynamic spectrum and the transition of the dispersion from the R-wave (about 17 min. in the beginning of event) to the L-wave (duration about 75 min.).

Interpretation

The possible mechanism of the generation for the first kind may be connected with the nonlinear effects. The linear processes of the interaction of

the EMIC waves with energetic anisotropy protons during many times cross of the source of such protons (the range near the top of the field line) lead to the increase their amplitude. Upon reaching a certain amplitude, EMIC waves propagating along the field line may decompose into an ion sound and EMIC wave of lower frequency propagating in the opposite direction in relation to the "mother" signal. Such a three-wave interaction has been considered by Feygin [1987] for explanation of the nature of the red-violet asymmetry in the production of pearl pulsations (Feygin et al. [1985]). The "mother" series gradually attenuates them during bouncing along the field line between the conjugated ionospheres. In the same time the "daughter" wave packet (with lower frequency in relation to the "mother" series) is amplified during many times crossing of the source and upon reaching the certain amplitude radiates an ion sound and EMIC wave of lower frequency, given generation series of Pc1 signals and so on. This process leads to a general "reddening" of the Pc1 spectrum ("cascade" of series Pc1 with decreasing frequency). The numerical estimates support this interpretation (Feygin F.Z., 1987). The example of a "red-violet" asymmetry in the production of "pearl" satellites based on the schematic sonogram (Sukkozero, October 17, 1977) presented on Fig. 4. The dots with the numbers represent the position of the given wave packet and its relative amplitude. The offered mechanism may be responsible for the formation of Pc1 pulsations with broadening down spectrum width

(Figure 1).

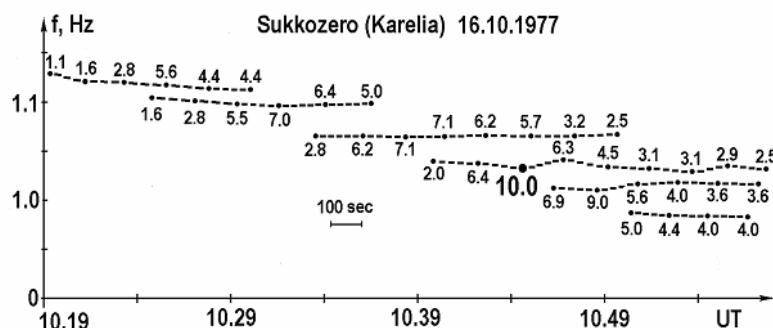


Fig. 4. The example of a "red-violet" asymmetry in the production of "pearl" satellites based on the schematic sonogram

The events with symmetrically broadening of the wave spectrum in relation to the beginning frequency of event we connected with the spectral broadening in the process of the quasilinear interaction EMIC wave with energetic anisotropic protons. A quasilinear approximation had been fruitfully used in the theory of the geomagnetic pulsations for explanation of the dynamic of the wave packet duration and fine structure of Pc1 spectrum (Feygin and Yakimenko, 1969; Gendrin et al., 1971; Feygin and

Kurchashov, 1975). Feygin and Kurchashov (1975) have done a numerical experiment allowing permanent control of the quasilinear stage of the Pc1' development: connecting amplitude of wave, duration of its excitation and dynamics of spectrum with parameters of plasma. They have shown that in the quasilinear stage takes place

symmetrically widening of the spectrum. A beginning of non-linear stage can be identified as a moment when the spectrum width begins to grow. During approximately 20 min. the spectrum width is increased in three times. The observed new type of Pc1 pulsation (Figure 2) is characterized by the narrow spectrum width $\Delta f/f_0 \sim 0.2$ at the beginning of the quasilinear stage and the broad spectrum width ($\Delta f/f_0 \sim 0.8$) in the processes of development of the event. Moreover, the amplitude of pulsations to the end of phase of spectrum broadening is increased. All dynamics of these parameters of new type of Pc1 pulsations correspond to the quasilinear development of the interaction of the EMIC waves with energetic anisotropy protons, given the broadening of the spectrum width and the increasing of the wave amplitude.

The third type Pc1 pulsations presented at the Figure 3 is characterized by the narrow spectrum width which look likes the goose's beak at the beginning of the event and the up broad spectrum width in the processes of development of the event ("the wing of the goose"). Unlike the classic pearl pulsations, the fine structure of the event at Figure 3 differs from the fan form. We can suggest that each wave pulse (structure element on the sonogram) is a new generation and has not bouncing between conjugated ionospheres. The idea of the Pc1 generation without the fan form corresponds to the model proposed in (Lyatsky and Plysova-Bakounina, 1986). This model assumes that Pc3-5 geomagnetic pulsations can affect the variation in parameters of energetic protons, e.g., enhance their anisotropy and density, and thereby provide conditions for development of ion cyclotron instability leading to generation of EMIC waves in form of Pc1 pulsations. In accordance with proposed model period of generation of Pc1 pulsations near the equatorial plane should be controlled by the period of long-period pulsations, the amplitude maximum of which is located in near-equatorial plane (symmetrical mode of standing wave of the field tube). In this case it is assumed that the sequence of ground-observed wave packets is caused only by a multiple generation of new wave packets near the equator plane with Pc 3-5 periodicity and structure elements on the sonogram should be parallel each other.

Discussion and conclusion

In the present study the new types of geomagnetic pulsations in the frequency range of Pc1 pearl waves with the dynamic spectra which have very narrow the spectrum width at the beginning of the event and the very broad spectrum width reach ($\Delta f/f_0 \sim 1$) in the processes of development of the event have been presented. It is seen from the sonograms on Figures 1-4, that all events have pronounced structure. Characteristic of the event on Fig. 3, unlike the Fig., 1, 2, 4 having typical fan structure of dynamic spectrum for Pc1 pulsations, is the absence of fan structure on the dynamic spectrum. Another interesting characteristic of the Fig.3 is that in the beginning of event the dispersion has the form of the R-wave, then there is an interval without dispersion and then the dispersion is transformed to dispersion of the L-wave. This event look likes the "goose" with a beak at the beginning of the event and the up broad spectrum width in the processes of development of the event ("the wing of the goose").

The possible mechanism of the generation for the first kind of Pc1 pulsations presented at Fig.1 we connected with a three-wave interaction considered by Feygin (1987). For the explanation of the symmetrically broadening of the wave spectrum in relation to the beginning frequency of event (Figure 2) we used the spectral broadening in the process of the quasilinear interaction EMIC wave with energetic anisotropic protons (Feygin and Kurchashov, 1975). The third type of Pc1, presented at Figure 3, has the dynamic spectrum with the structure elements parallel to each other. It means that the wave packets have not the bouncing between the hemispheres. In this case the event recorded in Oulu 18.06.1994 corresponds to the model proposed in (Lyatsky and Plysova-Bakounina, 1986). This model assumes that Pc3-5 geomagnetic pulsations can affect the variation in parameters of energetic protons, e.g., enhance their anisotropy and density, and thereby provide conditions for development of ion cyclotron instability leading to generation of EMIC waves in form of Pc1 pulsations. In accordance with proposed model period of generation of Pc1 pulsations near the equatorial plane should be controlled by the period of long-period pulsations, the amplitude maximum of which is located in near-equatorial plane (symmetrical mode of standing wave of the field tube).

In conclusion, we should like once again to emphasize that we have discovered the new interesting Pc1 signals which on the sonograms have very narrow the spectrum width at the beginning of the event and the very broad spectrum width reach ($\Delta f/f_0 \sim 1$) in the processes of development of the event. Sometimes these new types of Pc1 signals look like the goose's beak at the beginning of the event and the up broad spectrum width in the processes of development of the event ("the wing of the goose").

Acknowledgements. We acknowledge the financial support from the Russian Foundation for Basic Research, research grants No. 07-05-00774 and No. 08-05-00-617, the Program of Russian Academy of Sciences No. 16, part 3 "Solar activity and physical processes in the Solar-Earth system" and grant ISTC No. 3520 "Charged Particles Acceleration by Shock Waves in Space Plasma". K. P. acknowledges also the financial support of the EU's 5th Frame Programme under the IHP Programme (contract HPRI200100132). The authors acknowledge J. Kangas and T. Pikkarainen for the presented dynamic spectra of the Pc 1 pulsations.

References

- Cornwall, J.M., 1966. Micropulsations and the outer radiation zone. *J. Geophys. Res.*, 71, 2185-2199.
- Feygin, F.Z. and Yakimenko, V.L., 1969. Mechanism of pearl generation and development during cyclotron instability of the outer proton zone. *Geomagn. Aeronomie*, 9, 565-569.
- Feygin, F.Z. and Yakimenko, V.L., 1970. On the fine structure micropulsations of Pc1 type, *Geomagn. Aeronomie*, 10, 558-560.
- Feygin, F.Z., and Yu.P.Kurchashov, 1975. A Quasilinear Dynamics of Pc1 Geomagnetic Pulsations (Pearls), *J. Geomag. Geoelectr.*, 26, 539-548.
- Feygin, F.Z., Yu.P.Kurchashov, and V.A.Troitskaya, 1985. *Planet. Space Sci.*, 33, 271-273.
- Feygin, F.Z., 1987. Nature of the Red-Violet Asymmetry in the Production of "Pearl" Satellites. *Geomagn. Aeronomie*, 27, 908-909.
- Gendrin, R., Lacourly, S., Roux, A., Solomon, J., Feygin, F.Z., Gokhberg, M.B., Troitskaya V.A., Yakimenko, V.L., 1971. Wave packet propagation in an amplifying medium and its application to the dispersion characteristics and to the generation mechanism of Pc1 events. *Planet. Space Sci.*, 19, 165-194.
- Guglielmi, A.V., and Pokhotelov, O.A., 1996. *Geoelectromagnetic Waves*. IOP Publ. Ltd, Bristol.
- Jacobs, J.A., and T. Watanabe, 1964. Micropulsation whistlers, *J. Atmos. Terr. Phys.*, 26, 825-829.
- Kangas, J., Guglielmi, A., Pokhotelov, O., 1998. Morphology and physics of the short-period magnetic pulsations. *Space Sci. Rev.*, 83, 435-512.
- Kennel, C.F., Petschek, H.E., 1966. Limit on stably trapped particle fluxes. *J. Geophys. Res.*, 71, 1-28.
- Lyatsky V.B., and Plyasova-Bakunina, T.A., 1986. About effect of the geomagnetic pulsations Pc4 on pulsations Pc1, *Geomagn. Aeronomie*, 26, 802-806.
- Obayashi, T., 1965. Hydromagnetic whistlers. *J. Geophys. Res.*, 70, 1069-1087.
- Plyasova-Bakunina, T.A., Kangas, J., Mursula, K., Molchanov, O.A., Green, J.A., 1996. Pc1-2 and Pc4-5 pulsations observed at a network of high latitude stations. *J. Geophys. Res.*, 101, 10965-10973.
- Tverskoy, B.A., 1971. Dynamics of the Earth's Radiation Belts. NASA, Technctranslation, F-635.