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Pulsating aurora - a review

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Abstract In this review, the observational facts about pulsating aurorae are summarized and discussed in the frame of the recent development of the theories which intend to explain the mechanism of auroral pulsations. Although new data are available some key observations in the magnetosphere are still missing in order to identify the wave mode to precipitate electrons into the atmosphere and in order to understand the role of magnetospheric plasma in producing pulsating aurora. It appears that the Coroniti-Kennel or micropulsation theory needs to be re-visited although the so-called flow cyclotron maser model seems to explain many of the characteristics of auroral pulsations.

Key words pulsating aurora, particle precipitation, auroral zone, energy spectrum, precipitating electron.

1 Introduction

By definition pulsating aurora is an aurora which undergoes at least one full cycle where there is first a rapid increase, then a rapid decrease in intensity. Pulsations are usually repetitive and often quasiperiodic or irregular and do not show shear motion phenomena. Their fluctuation period is typically in the period range of 0.3~30 seconds and the intensity seldom exceeds 10 kR at 427.8 nm wavelength. Yamamoto (1988) has critisized the classical concept of "period" which according to his observations does not mean much. He instead proposes that the luminosity fluctuations should be treated as a series of individual isolated pulses where the pulsation "on" time is the most essential quantity.

According to one of the three major classifications in the International Auroral Atlas, "pulsing aurora" shows fast, often periodic changes in intensity. The period ranges from a fraction of a second to the order of minutes. Pulsing aurora can be further divided into four subclasses: pulsating, flaming, flickering and streaming. Pulsating aurora which is the most common is characterized by intensity variations over the whole auroral form. An idealized stationary pulsating aurora can be defined by the equation:

$$I(r,t)=I_s(r)I_t(t) \tag{1}$$

where $I_s(r)$ is the spatial function and $I_t(t)$ represent the temporal changes over the form (Omholt, 1971). In general, the geometrical function $I_s(r)$ varies slowly in time and it is more proper to write:

$$I(r,t)=I_s(r,t)I_t(t) \tag{2}$$

Forms of pulsating auroras can be divided into three groups: arcs , arc segments and patches. Patches are the most common form. It appears that it is important to classify pulsating auroras also according to their motional features. There are stable and active pulsating forms. Yamamoto and Oguti (1982) identified still several subgroups: pure pulsation, expansion, streaming, propagating, flaming and flash. It is obvious that the complicated terminology makes it somewhat difficult to compare the results of different authors.

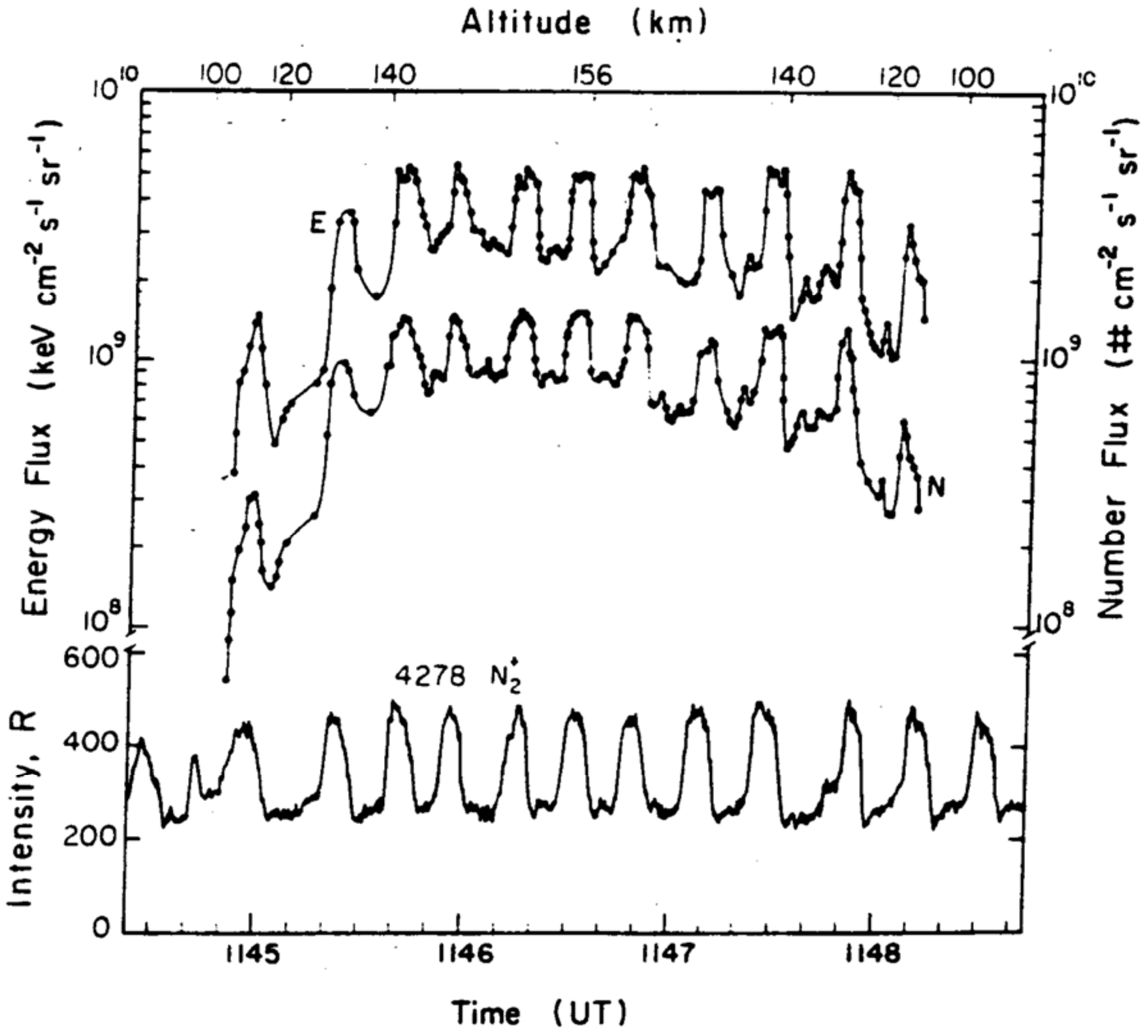
There have been three major trends in the studies of pulsating aurora during recent years: (a) As many of the principal characteristics of pulsating aurora are quite well known there is a transition from qualitative studies to quantitative ones. Several theories of pulsating aurora have been introduced. (b) More attention have been paid to high latitude dayside auroral pulsations than before, especially because of the observations in Antarctica. There are some indications that the existing mechanisms need to be modified to some degree due to this development. (c) The multicorrelation investigations have become more important as e. g. many ionospheric parameters are now available.

Several reviews of pulsating aurora have been given in the past by Omholt (1971), Vallence Jones (1974), Royrvik and Davis (1977) , Johnstone (1978, 1983), Tanskanen (1991) and Oguti (1992). In this review recent developments and trends are taken into account and some major challenges are pointed out. We try to find the main observational facts which are generally agreed by comparing the most recent development with the reviews by Johnstone (1983) and Oguti (1992).

2 Observational facts about pulsating aurorae

2. 1 Pulsating aurora is caused by a temporal modulation of the intensity of the high energy precipitating electron flux

Still in 1978 Johnstone (1978) wrote: "We assume that pulsating auroras are caused by the precipitation of electrons from closed field lines, and that the pulsations are the result of a modulation of the intensity of the electrons in the precipitating beam." Later, mainly on the basis of the observations presented by McEwen *et al.* (1981) and shown in the Fig. 1, Johnstone (1983) made a stronger statement: "Pulsating aurora is caused by a temporal modulation of the intensity and energy spectrum of a precipitating electron beam." Oguti's conclusion in 1992 is: "It is quite certain that pulsating aurora is originally caused by flux modulation of precipitating electrons."



February 15, 1980; Southend

Fig. 1. The measured electron energy influx E and number flux N during a rocket flight in pulsating aurora. The intensity of the N_2^+ 4278 Å (0,1) band emission measured with a ground-based photometer is showm below. (McEwen *et al.*, 1981)

A somewhat cautious formulation by Johnstone (1978) and Oguti (1992) may be due to an alternative view presented by Luhmann (1979) and by Stenbaek-Nielsen (1980) that the ionosphere may play an important role in the generation of pulsating aurora. However, both Johnstone (1983) and Oguti(1992) present quite strong arguments against such a possibility. There is some further evidence about thin pulsating patches introduced by Stenbaek-Nielsen and Hallinan(1979) by Wahlund *et al.* (1989) although Kaila *et al.* (1993) were not able to identify such layers by using similar, most sophisticated incoherent scatter radar measurements.

Many of the measurements of the energy spectrum of precipitating electrons to pulsating aurora indicate that the modulation occurs mainly in the high-energy part of electron fluxes but covering a broad energy range as summarized by Oguti (1992). It is also important to notice that there is an ample evidence that there is also a temporal modulation of the energy spectrum associated with pulsating aurora, see e. g. Brown and Weir (1967), Kangas (1968), McEwen *et al.* (1981) and more recently by Kaila and Rasinkangas (1989) and Bösinger *et al.* (1995*). In this connection it is important to point out that there is no prominent intensity maximum at any fixed energy of the precipitating electrons causing pulsating aurora in contrast to that causing auroral arcs as outlined by Oguti (1992).

2. 2 *The modulation of the electron beam takes place near the equatorial plane*

Bryant *et al.* (1971) have shown by rocket measurements that pulsations in lowenergy electrons lag behind those in higher energy electrons. After some assumptions it was concluded that the modulation region of the precipitating electrons is located near the geomagnetic equatorial plane.

The same energy dispersion has also been found in observations of the 3 ± 1 Hz modulation (Lepine *et al.*, 1980). This modulation is a persistent feature of many pulsating auroras: according to Royrvik and Davis (1977) it occurs in more than 50% of pulsating auroras.

Conjugate studies of pulsating aurora have given a further support that the modulation takes place in the equatorial plane (see Fujii *et al*, 1987 and references therein). It has been shown that "an individual pulsating aurora in one hemisphere has a topologically corresponding counterpart in the other hemisphere" as stated by Fujii *et al.* (1987).

It is remarkable that any major process causing the modulation of the electron beam is effective in the equatorial plane and in a broad range of pulsation periods. It has been most important to find any correlated phenomena with pulsating aurora in the equatorial plane. Both Johnstone(1983) and Oguti(1992) tried to identify such phenomena. It appears that only pulsating ELF-VLF waves can be firmly correlated with pulsating aurora. In the ULF range, any significant compressional hydromagnetic waves seem to be absent in the equatorial plane conjugate to pulsating aurora (Oguti *et al.*, 1986).

It has been most puzzling that no clear evidence of a pulsation in the electron fluxes in the equatorial plane has been given. As was pointed out by Johnstone (1983) it may be that any pulsations may occur in a small part of the electron distribution in or near the loss-cone. In such a case there are difficulties to detect fluctuations by satellites.

2. 3 *Pulsating patches drift in the direction of the magnetospheric electric field drift*

As was mentioned above pulsating aurora may show different types of motions. One of the most interesting motions is the longitudinal drift of pulsating patches along the auroral zone. It has been shown conclusively by Oguti *et al.* (1981), Scourfield *et al.* (1983) and Nakamura and Oguti (1987), see also Oguti (1992) that pulsating patches in the dusk sector drift to the west while they drift to the east in the morning sector.

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* Bösinger, T., Kaila, K., Rasinkangas, R., Pollari, P., Kangas, J., Trakhtengerts, V., Demekhov, A. and Turunen, T. (1995): An EISCAT study of a pulsating auroral arc: simultaneous ionospheric electron density, auroral luminosity and magnetic field pulsations. *J. Atm. Terr. Phys.*, in press.

These observations indicate that such motions are due to the $\boldsymbol{E}\times\boldsymbol{B}$ drift under the magnetospheric electric field.

2. 4 The shape of a pulsating patch may persist over many cycles

One important characteristic of pulsating patches is their stability. The shape of a pulsating patch may persist during many pulsation periods, especially in the morning sector as pointed out by Oguti (1992). One more important characteristic of pulsating patches is that even neighbouring patches pulsate in an independent way from each others. Oguti (1976) pointed out that pulsating patches may be considered as the ionospheric projections of cold plasma enhancements in the magnetosphere. There are now direct observations of such ducts by Koons (1989).

2. 5 There is no definite latitude dependence of the pulsation period

Oguti(1992) states in his critical paper that many people believe that the pulsation period is longer at higher latitude. Johnstone (1978) summarizes also that "the mean period is not related geometrically to the magnetosphere". On the other hand, Thomas and Rothwell (1979) show some evidence that the period of optical auroral pulsations increases with increasing latitude in individual displays of pulsating patches. It is remarkable that the period and its variation match the bounce period of a 2 keV electron on the same field line (see Fig. 2). The periods reported by Thomas and Rothwell (1979) are typically below 10 seconds. Moreover, Brekke and Pettersen (1971) and Craven and Burns (1990) report that pulsation periods of high latitude pulsating aurorae are typically 20~30 seconds compared to average auroral zone variations below 10 seconds.

It may appear that the question about the latitude dependence of pulsation period still remains unsolved. However, Oguti (1992) presents strong arguments which show that the period of pulsating aurora does not depend on latitude, at least in the major range of pulsation periods.

2. 6 Pulsating aurora is not only the recovery phase phenomenon

Oguti (1992) critisizes also a common belief that pulsating aurorae occur during the recovery phase of the auroral substorm. There is, however ample data to show that pulsating aurorae are initiated during the expansion phase as summarized by Oguti (1992). It is also evident that pulsations may occur during low magnetic activity. Thus pulsating aurorae cannot be taken as any significant indicator of the recovery phase of substorms.

In searching possible sources of pulsations different processes at different phases of substorm must be taken into account as discussed by Demekhov and Trakhtengerts (1994). During the breakup phase auroral pulsations demonstrate in some way the dynamical features of the particle acceleration mechanism and of the changing configuration of the geomagnetic field. During the recovery phase of the substorm processes of more stationary character dominate and energetic electrons are drifting from the midnight sec-

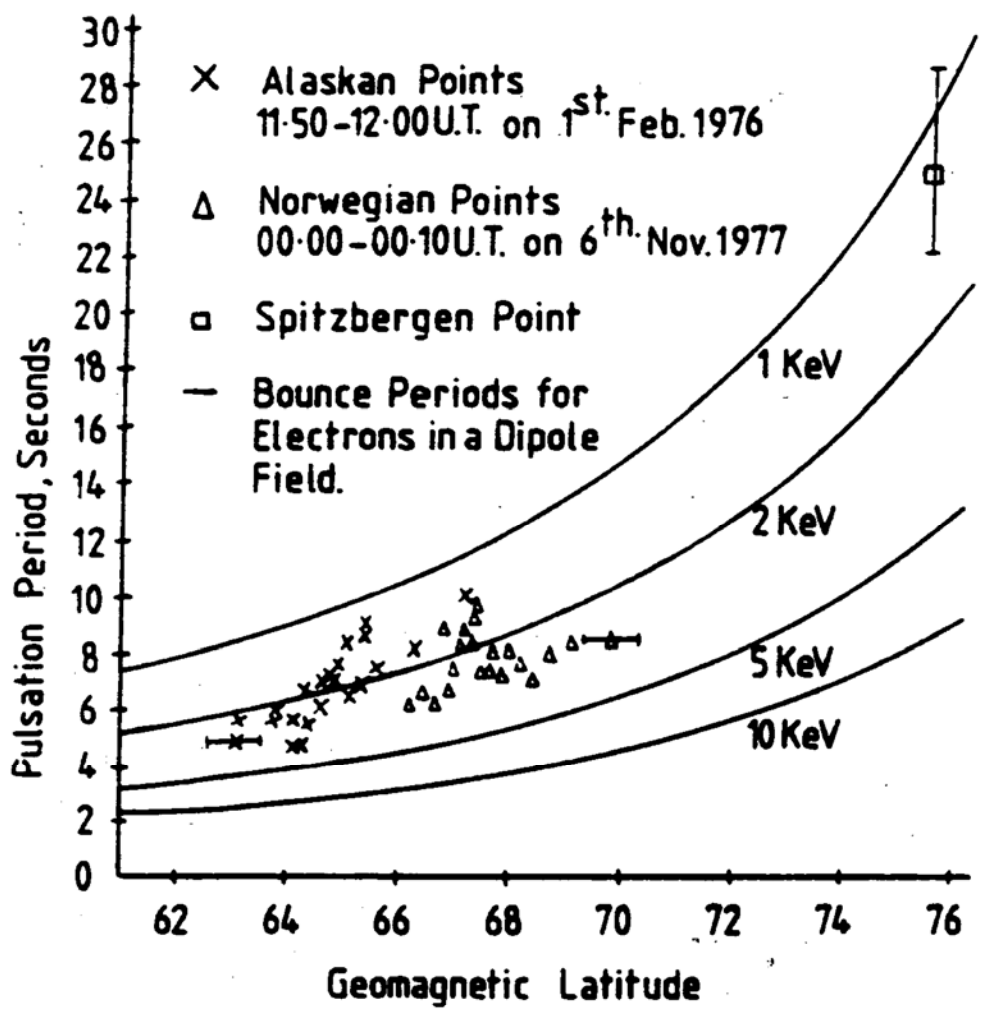

Fig. 2. Variation of patch pulsation period with geomagnetitc latitude. The variation of bounce period with latitude for electrons with energies of 1, 2, 5, and 10 keV in a dipole field is shown for comparison. (Thomas and Rothwell, 1979)

tor to the morning sector.

2. 7 *Correlation between pulsating aurora and ULF waves is not simple*

It is generally accepted that there is a link between magnetic and auroral pulsations. This relationship is, however hard to be established because magnetometers integrate over an extended area while optical instruments isolate individual patches. On the basis of ground observations it has been shown quite conclusively that magnetic field variations below the pulsating aurora are due to the conductivity changes in the ionosphere caused by the pulsating electron precipitation as summarized by Oguti (1992).

Oguti *et al.* (1986) report that any significant compressional HM wave is absent in the equatorial region conjugate to pulsating aurora. However, Xu *et al.* (1993) have concluded on the basis of ground observations that ULF MHD waves modulate auroral emissions, typically in the frequency range of 1~4 mHz.

On the basis of an extended data set it has been concluded that the intensity of VLF emissions in the auroral zone can be modulated at any period of magnetic pulsations observed on the ground (Manninen, personal communication). Such modulations occur far most often in the morning-to-noon sector of the auroral zone. An example of a close correlation between the variations in magnetic field and VLF chorus intensity in the P_{c3} period range is shown in Fig. 3 (Manninen *et al.*, 1995*).

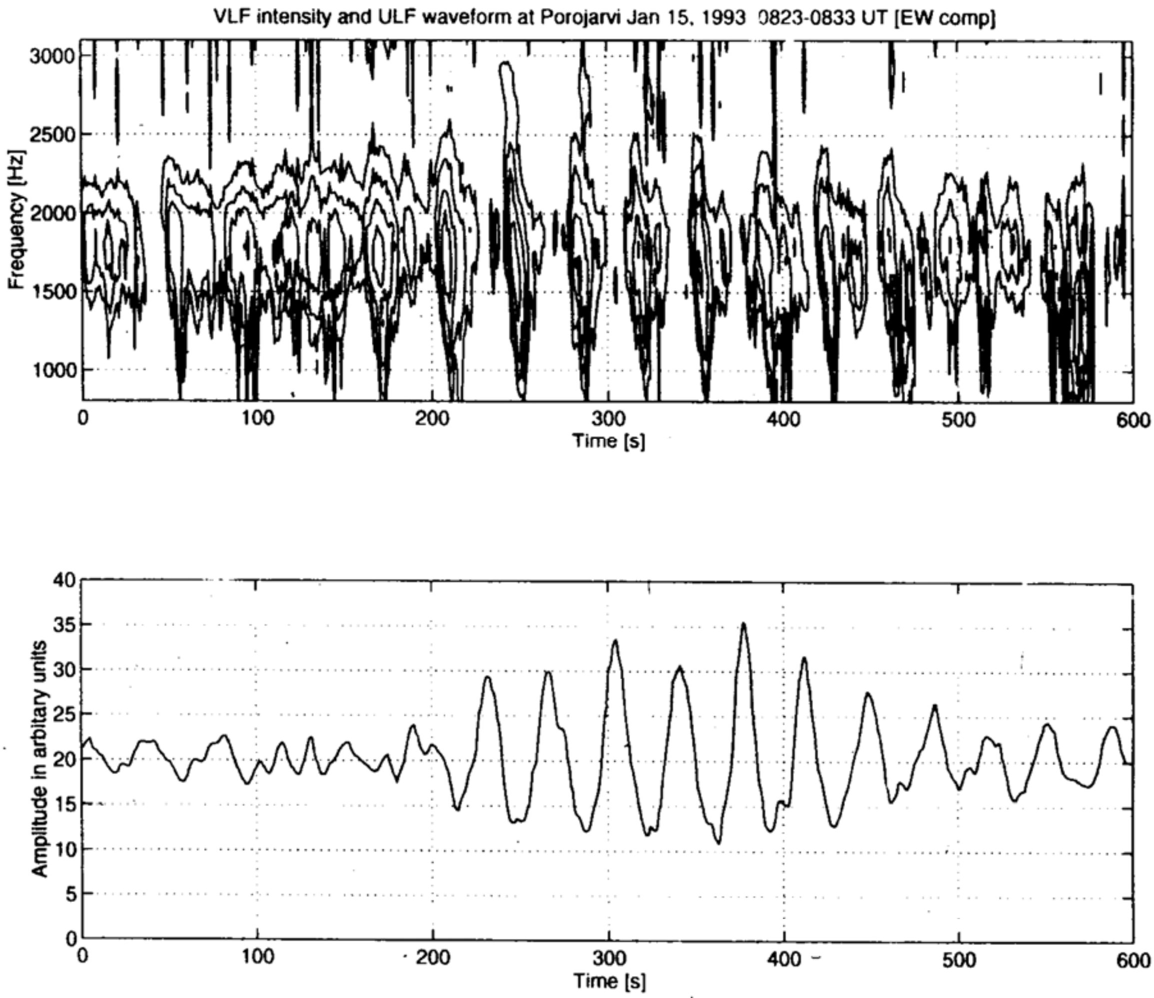

Fig. 3. Intensity variations of VLF chorus bursts and EW component of magnetic field as measured in an auroral-zone station Porojärvi, Finland on January 15, 1993. (Manninen *et al.*, 1995*)

3 Possible mechanisms causing pulsating aurora

As the period range of auroral pulsations is very large and when taking into account the above mentioned observational facts it is most probable that no single mechanism is

* Manninen, J., Turunen, T., Kultima, J. and Titova, E. (1995): Correlating optical emissions, quasi-periodic VLF emissions and magnetic P_{c3} pulsations. *Geomagn. Aeron.*, in press.

able to account for the whole phenomenon. It may be that in searching the mechanisms it is good to classify the pulsations to three different period ranges: period less than 1 second, from 1 second to some tens of seconds and longer (Oguti, 1992).

As was mentioned above pulsating aurora can be related to pulsating ELF emissions in the equatorial plane. ELF and VLF waves in the magnetosphere, i. e. hiss and chorus emissions are electromagnetic waves below the electron gyrofrequency propagating in the whistler mode. They can scatter electrons from trapped orbits to be precipitated into the atmosphere. The scattering takes place over a small range of latitudes around the equatorial plane as summarized by Johnstone (1983). If the intensity of waves varies a modulation in the precipitating electrons is expected. The central question is how the modulation is imposed on the electron beam?

There are two major proposals which have been more widely discussed in the literature: the C-K or micropulsation theory forwarded by Coroniti and Kennel (1970) and the relaxation oscillator mechanism introduced by Trefall and Williams (1979) and Davidson (1979,1986). The latter mechanism was further developed by Trakhtengerts and co-workers (Demekhov and Trakhtengerts, 1994) and the flow cyclotron maser model has been formulated which seems to be one of the most successful theories of pulsating aurora, especially in the case of pulsating patches during the recovery phase of the substorm.

3. 1 The C-K or micropulsation theory

The basic idea behind the theory proposed by Coroniti and Kennel (1970) is that the hiss intensity and thereby the intensity of the precipitating electrons varies as the equatorial magnetic field pulsates. It was estimated that an increase of 2% in the magnetic field would be enough to modulate the electron beam by a factor of 2.

The C-K theory has usually been disregarded in the most recent papers mainly because of the absence of any compressional mode HM wave in the equatiorial plane conjugate to the region of pulsating aurora. However, the observations reported by Xu *et al.* (1993) as mentioned above may be a good reason to re-visit the micropulsation theory. Oguti (1992) concludes also that a coupling between magnetospheric HM waves and the growth of VLF waves may exist in the period range of longer than 1 minute and is due to a further study. The observations shown here in Fig. 3 could also be understood in the frame of the micropulsation theory as the P_{c3} magnetic pulsations mostly originate in the solar wind.

3. 2 The relaxation oscillator mechanism

In the C-K theory an external agent is needed to modulate the electron beam. Trefall *et al.* (1975), Trefall and Williams (1979) , Davidson (1979, 1986) have introduced an idea that the precipitation pulsations of trapped magnetospheric electrons are due to the very nature of the wave-particle interaction which precipitates energetic electrons in the morning sector of the auroral zone.

The growth of scattering waves is assumed to be controlled by the number of trapped electrons which can resonate with the waves. Due to the precipitation the number of resonating electrons decreases below that necessary to sustain the wave growth and the waves are quenched. Thereafter, pitch angle diffusion gradually restores the particle distribution and the wave growth starts again. In this way, a relaxation oscillation occurs and precipitation pulsations are expected. Fig. 4 illustrates a full cycle of relaxation oscillator as viewed in the electrons pitch angle distribution (see Davidson, 1986).

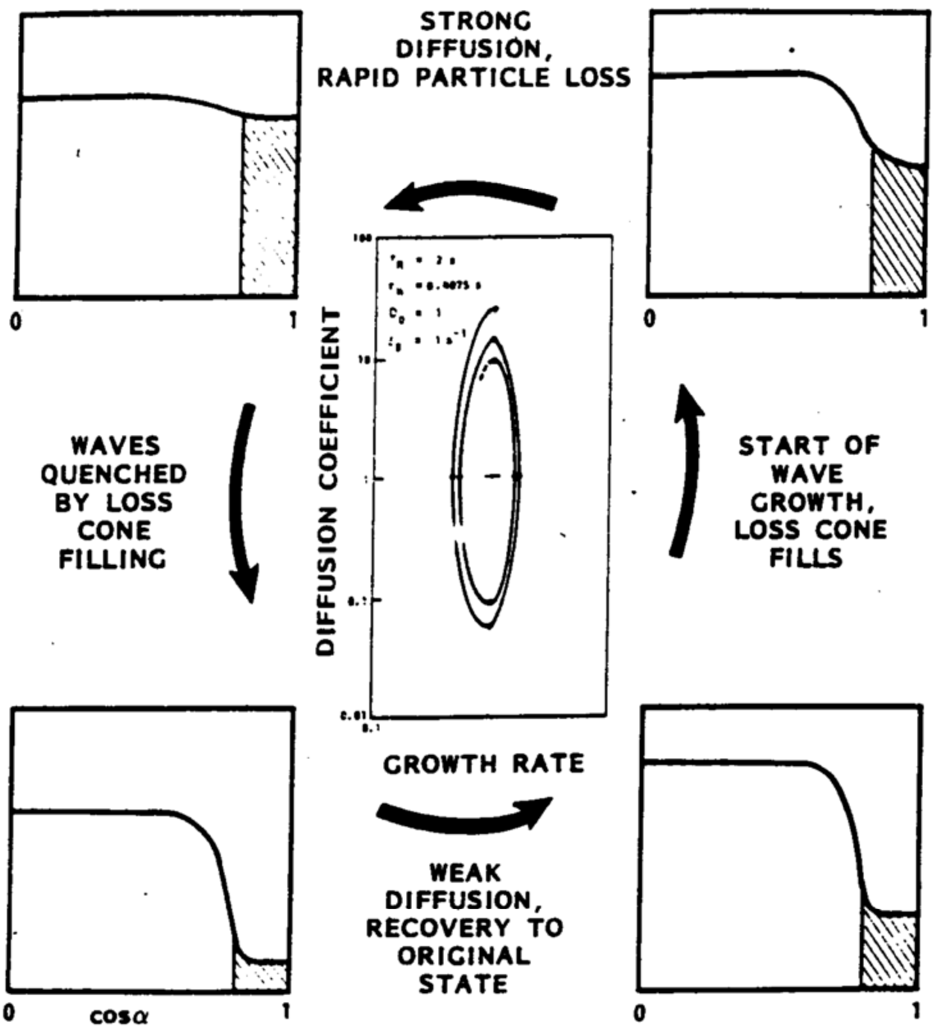

Fig. 4. The nonlinerar wave growth / particle precipitation relaxation oscillator. The figure reads counterclockwise and indicates successive stages within a single pulsation. (Davidson, 1986)

Davidson (1979) showed that pulsations are possible for both hiss and chorus waves and a wide range of periodicties can be generated . Because of the statistical fluctuations in the process variations in the period of pulsations are expected. Davidson (1979) and Johnstone (1983) discussed also the importance of patches of cold plasma to intensify the wave-particle interaction and to serve as a duct for wave propagation to ensure the observed stability of morning pulsating auroral patches.

The first version of the theory by Davidson (1979) predicted too long periods(30~

100 s) for most pulsating auroras. Davidson (1986) concluded that it was mainly because the VLF wave growth rate was assumed to be controlled principally by the total trapped particle flux. The revised theory presented by Davidson (1986) emphasizes the structure of the loss cone as the main reason controlling the VLF wave growth and the periods of 3 to 30 seconds are predicted.

Davidson (1986, 1990) pointed out that many of the observational facts agree with the expectations of the nonlinear relaxation oscillator model. At the same time he lists several open problems such as the association of temporal pulsations and complex spatial structures, identification of proper wave modes in scattering of electrons and the role of the magnetospheric plasma.

3. 3 Flow cyclotron maser model

Trakhtengerts *et al.* (1986) and Demekhov and Trakhtengerts (1994) made some critical comments on the above mentioned models and the so-called flow cyclotron maser model to be applied on pulsating patches during the recovery phase of the substorm was developed. Critical comments are mainlly due to the equation for pitch angle anisotropy evolution in the course of the cyclotron instability development.

In this model, the duct with enhanced plasma density serves as a resonance cavity. Drifting energetic electrons injected during the substorm are the source of fresh particles into the process of wave-particle interaction. Modulation in the cyclotron instability is caused by these new resonance electrons. The pulsation "on"-time is determined in this model by nonlinear development of the cyclotron instability in the duct. The period of pulsations is proportional to the drift time of electrons across the instability region.

Recently Bösinger *et al.* (1995) made a multi-instrumental study of auroral pulsations in the morning sector which supports the flow cyclotron maser model. It is interesting that the pulsations with a period of about 10 seconds were superimposed on slower pulsations with a period of about 60 seconds. Bösinger *et al.* (1995) conclude that two independent mechanisms to produce variations in auroral luminosity can be in operation at the same time: long period pulsations can be attributed e. g. to largescale variations of the magnetic field in the magnetosphere whereas the fast variations can be explained in terms of the self-oscillating process of the whistler cyclotron instability in the magnetosphere.

4 Concluding remarks

The aim of this review paper was to summarize the observational facts which are commonly accepted and to outline the basic principles of the most important theories of pulsating aurorae. It is evident that the most interesting development during last ten years has taken place in the theory but some new observations seem to open also promising perspectives.

The most recent theories can account for many of the observed characteristics of pulsating aurorae. At the same time some critical data are still missing in order to test them in more detail. Especially, high-resolution measurements of wave-particle interactions and cold plasma structures in the magnetosphere during pulsating aurorae are most urgently needed. Multi-instrumental ionospheric data have been useful and should still be collected in order to understand the role of the ionospheric plasma. A global study of the occurrence of auroral pulsations during different phases of the substorm and in different local time sectors of the auroral zone should also be made.

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