Journal of Atmospheric and Solar-Terrestrial Physics 69 (2007) 1623–1634

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Satellite observations of Pc 1 pearl waves: The changing paradigm

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Received 23 October 2006; received in revised form 21 February 2007; accepted 28 February 2007
Available online 12 July 2007

Abstract

Pc 1 pearls have been observed on the ground for about 70 years. During this time numerous publications have been written on the various properties of Pc 1 pearl waves, the related theory, and possible applications. Pc 1 waves with a clear pearl structure are only a fraction of all Pc 1 waves observed on ground, and this fraction depends on the latitude of observations, increasing from high to low latitudes. In fact, the spatial and temporal occurrence of Pc 1 pearls is closely connected with the location and development of the plasmapause. While it has been known roughly 40 years that Pc 1 waves are electromagnetic ion cyclotron waves generated by anisotropic, energetic ions in the near-equatorial magnetosphere, the formation of pearl structure is still largely in question. In situ observations of Pc 1 waves in the Earth's magnetosphere have been made since the 1970s by various satellites in different orbits. However, satellite observations of clear Pc 1 pearls are still rather few. Here we review a few crucial satellite-based observations of Pc 1 pearls, and evaluate their contribution to the understanding of pearl formation. We show that the long-held paradigm of the bouncing wave packet model is in serious contradiction with satellite observations and therefore outdated. Instead, observations support the idea that Pc 1 wave growth rate is successively modulated at the equator by long-period ULF waves.

Keywords: Pc 1 pulsations; EMIC waves; Satellite observations

1. Introduction

Pc 1 pulsations were first observed rather serendipituously as a result of appropriate resonance characteristics of the new LaCour type magnetometers installed at a number of observatories in the 1930s (Harang, 1936; Sucksdorff, 1936). However, the new phenomenon did not attract much attention until the early 1960s when more refined observational methods and, after Alfvén's ground-breaking introduction of MHD waves, specific physical theories for different types of plasma waves had been developed. Since then, it is known that Pc 1 pulsations are electromagnetic ion cyclotron (EMIC) waves generated in the equatorial magnetosphere by the cyclotron instability of energetic ions (in the energy range of ~10−100 keV) with an anisotropic energy distribution (Brice, 1965; Cornwall, 1965). The typical frequency range of waves varies typically from fractions of Hz to a few Hz.

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doi:10.1016/j.jastp.2007.02.013

A part of Pc 1 pulsations, so called structured Pc 1 waves or Pc 1 pearls (Sucksdorff, 1936), are characterized by regular amplitude variations forming a series of separate wave packets or pearls (see Fig. 1). Pearls are the most common form of Pc 1 waves at low to mid-latitudes (Fraser-Smith, 1970), and are observed preferably in the morning sector. They also occur at high latitudes (Troitskaya and Guglielmi, 1970; Fukunishi et al., 1981; Murusula et al., 1994a) but the pearl structure there is often less clear or less systematic, and the majority of Pc 1 waves at high latitudes are unstructured, i.e., do not have a clear repetitive structure at all.

In addition to innumerable ground-based studies of Pc 1 waves, the corresponding waves in the magnetosphere, the EMIC waves, have also been observed by various satellites. The satellite studies of Pc 1 waves have verified the cyclotron instability as the generation mechanism, and given more precise information on the different statistical and morphological properties (e.g., spatial distribution, temporal occurrence, frequency bands, polarization, etc.) of these waves that can be obtained by ground observations alone. This is particularly true for the spatial occurrence of Pc 1 waves where satellite observations (Taylor and Lyons, 1976; Fraser et al., 1984, 1989; Erlandson and Anderson, 1996) have verified the ground-based result (Roth and Orr, 1975; Lewis et al., 1977; Webster and Fraser, 1985) of the close connection of Pc 1 pearls with the plasmapause, and the preferred occurrence of unstructured Pc 1 waves in the high-latitude post-noon magnetosphere (Anderson et al., 1992). Also, extensive satellite–ground conjunction studies have confirmed the overall agreement of observations of Pc 1 waves in space and on ground, quantifying the ground visibility of these waves (Bräysy and Mursula, 2001).

However, there are only a few cases of satellite observations of structured, repetitive EMIC waves so far. Even more rare are events where the structured EMIC waves could be verified to correspond to ground-based Pc 1 pearls, or where a clearly dispersive pearl-type structure can be seen in satellite observations. In this review, we concentrate on a few crucial satellite observations of Pc 1 pearls and the implications of these observations upon theories of pearl packet formation. However, we will start with some notes on the history of Pc 1 pearls, and discuss the two leading theories of pearl formation.

2. Pearl dispersion and VLF whistler analogy

The first idea to explain the Pc 1 pearl structure was the bouncing wave packet (BWP) model (Jacobs and Watanabe, 1964; Obayashi, 1965), according to which the repetitive pearl structure is generated by a wave packet bouncing along the field line between opposite hemispheres, losing part of its energy when reflecting from the ionospheres and gaining energy when traversing through the equatorial growth region. The BWP model was based on the intuitive and highly suggestive analogy between Pc 1 pearls and VLF whistler waves. (Due to this analogy, Pc 1 pearls are sometimes even called ion

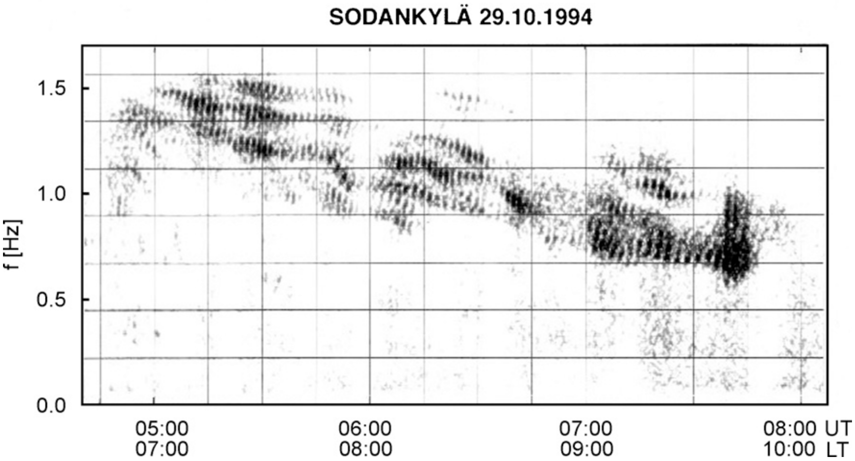

Fig. 1. Dynamic spectrum of a versatile Pc 1 pearl event observed at Sodankylä, Finland, in October, 29, 1994. Note the random, non-systematic variation of dispersion and the joining and separation of the different pearl bands.

whistlers.) Both waves depict clear wave packets which have a dispersive structure. In VLF whistlers, higher frequencies are faster than lower frequencies, leading to a typical decreasing pitch. Pc 1 pearls have mostly an opposite dispersion to VLF whistlers, depicting typically a slightly increasing pitch (see Fig. 1).

However, when studied in more detail, there are dramatic differences between whistlers and Pc 1 pearls, making this analogy quite unfortunate. First, there is a clearly identified source (lightning strokes) which initiates the whistler wave trains. This source can also occasionally be seen in the recordings. On the other hand, the cause for a start of a Pc 1 pearl necklace is not unique (ion injection, pressure pulse, etc.) and can only seldom be identified. Anyway, the cause of Pc 1 pearls is not in the atmosphere as for VLF whistlers, but in the high-altitude (equatorial) magnetosphere.

Also, the spectral properties of VLF whistler waves and Pc 1 pearls are very different. The total frequency decrease during a VLF whistler is very large compared to its momentary frequency width, showing the VLF whistler as a very clear dispersive pattern in the dynamic spectrum. Also, the temporal evolution of dispersion of whistlers is significant. The change in dispersion is so clear that the different bounces can be easily separated from each other, and the order of the bounce can be determined from the observed dispersion. However, the whistler retains its frequency range during the event. The number of bounces of an individual VLF whistler remains quite small (maximum 10).

The dispersion properties of Pc 1 pearls are very different. A typical Pc 1 pearl necklace contains tens of pearls, and the average frequency and even the full frequency range of pearls may change dramatically during the event (see Fig. 1). Pc 1 pearls are typically slightly dispersive, mostly with increasing slope. However, pearl dispersion does not increase with time systematically, contrary to VLF whistlers, but remains the same from one pearl to another, or fluctuates rather randomly (see Fig. 1). So, there is no support from the pearl dispersion properties for the BWP model which requires that dispersion increases systematically during the pearl necklace as a result of the increasing path of the BWP.

Quite often one finds several simultaneous Pc 1 pearl bands, as in Fig. 1. Typically, the individual pearl bands are rather narrow and the pearls are repeated independently in the different bands. The number of bands may also vary in time, as in Fig. 1, where up to five simultaneous bands are seen to coexist. Two bands may sometimes join together, or one band can split into two bands. Also, the spectral widths of the bands may experience sudden changes. Fig. 1 depicts an interesting temporal development where initially two separate bands at about 0500 UT join together at about 0520 UT, forming a number (some 5–6) of coherent pearls, and are then separated again. Another interesting change occurs at the end of the depicted time interval at about 0740 UT where the spectral width of a pearl band is suddenly more than doubled, extending into the frequency range where another band existed only shortly before. In both cases joining/extension occurred when the amplitude of the waves was greatly increased. Such fairly typical observations and properties of Pc 1 pearl necklaces are very hard, if not impossible to explain in terms of the BWP model.

The BWP model had the paradigm status of Pc 1 pearl formation for long. This status was mainly based, aside of the erroneous analogy with VFL whistlers, on one claimed piece of evidence: the early observation that the Pc 1 wave packets in conjugate locations at the opposite ends of a field line are seen alternately (Yanagihara, 1963; Gendrin and Troitskaya, 1965; Obayashi, 1965). Admittedly, such an anti-phasing would be naturally explained by the BWP model. However, anti-phasing is not unique to the BWP model since other models can also accommodate this property. Moreover, the early observations were made during the "analogue era" when measurement and analysis conditions (timing accuracy, spectral analysis methods, etc.) were still rather elementary. Taking into account the rather long length (about 30 s; see later) and frequent repetition (repetition period ranges from several tens of seconds to a couple of minutes) of Pc 1 pearls, it must have been quite difficult to study the phasing of packets at that time (see also Fig. 1). Moreover, the early evidence is rather qualitative and preliminary (as even the title of Gendrin and Troitskaya, 1965 says), rather than quantitative and statistically conclusive. Note also that some early (Gendrin and Troitskaya, 1965) and more recent (Mende et al., 1980) studies have even found that the phase difference between the wave packets is not consistently 180°, as required by the BWP model, but can systematically deviate from it. Accordingly, there is no conclusive evidence in favor of the BWP model.

3. Equatorial modulation of Pc 1 wave growth

In addition to the BWP model, two other, alternative models of pearl formation have been suggested which both include the idea of an equatorial modulation of Pc 1 growth rate but by very different mechanisms. Therefore, these models can be called equatorial growth modulation (EGM) models. One of the EGM mechanisms is based on the fact that the bounce period of ions with energies suitable for Pc 1 production are close to the observed wave repetition period (for a more detailed discussion of this model, see Erlandson et al., 1992). For example, the appropriate proton energy corresponding to the observed wave repetition period ranges from about 35 keV to about 120 keV, depending on the ion pitch angle. Accordingly, phase-bunched ions bouncing from one hemisphere to another would produce one wave packet at every equatorial crossing. However, the wave repetition period on the ground would be the same as the ion bounce period, not doubled, since the resonance condition requires an antiparallel motion of ions and waves, and only every second crossing would produce a wave packet propagating in the same direction. Alas, the main problem for this model is to develop a detailed physical theory for the phase bunching of ions. Actually, in this model, the problem of packet formation is just moved from waves to particles. Moreover, several basic properties of ground-based Pc 1 pearls discussed above, such as the many simultaneous pearl bands and their temporal evolution, are very difficult to explain by this model. Therefore, it is very unlikely that the ion bunching model is the cause of Pc 1 pearl formation.

The other EGM model is based on the idea that plasmas are most typically in a state of marginal stability (Gail, 1990). Thus, even rather small perturbations of some critical plasma parameters could lead to instability, raising and lowering the Pc 1 wave growth at the equatorial source region above and below the critical rate. Since the ion cyclotron instability is among the most important mechanisms (perhaps even the very most important mechanism) for plasma to restore stability, the suggested process would be very natural and common. This important fact also explains the exceedingly frequent occurrence of EMIC waves in many different plasma environments, for example, in all those systems that have been thoroughly studied, like the solar atmosphere and the Earth's magnetosphere.

Many satellite studies have shown (Mauk and McPherron, 1980; Erlandson et al., 1990; LaBelle and Treumann, 1992; Fraser et al., 1996; Mursula et al., 2001) that the Pc 1 waves reflected from the ionosphere are very weak, less than about 10–20% of the downward directed wave amplitude (Erlandson et al., 1992). Thus, the reflected EMIC waves can hardly have any effect on the equatorial plasma parameters. Accordingly, the BWP model is not an EGM model although the waves are supposed to be amplified there. Thus, in the BWP model the waves must be continuously produced at the equator, not only when the reflected packet arrives there. Since plasmas tend to reach local equilibrium quite rapidly, it is questionable if the plasma is still out of equilibrium and if waves can still be amplified after one packet bounce, since plasma may already have reached stability by the time when the packet returns to the equator. Even more difficult it is to think of continuous wave generation during the long pearl necklaces lasting for several hours, sometimes even days. So, the BWP model has this serious problem of a need for persistent wave generation, making it unphysical and inherently inconsistent.

In contradiction to the BWP model, such a problem does not appear in any EGM model where plasma is repeatedly set to an unstable state by the modulating effect and the EMIC waves are produced only temporarily, as an immediate consequence of this modulating disturbance. Plasma can quickly recover stability until the next disturbance makes it unstable again and so on.

The long-period ULF waves can act as such a modulating agent which periodically affects some plasma parameters (e.g., plasma density, magnetic field strength, etc.) that are critical for EMIC wave growth. This would naturally lead to repetitive wave packets at the ULF wave period (or twice the period in the case of an antisymmetric wave). During the last 10 years, an increasing amount of evidence has been reported by both ground observations (Plyasova-Bakounina et al., 1996) and by satellite observations (Fraser et al., 1992; Rasinkangas et al., 1994; Mursula et al., 1997; Rasinkangas and Mursula, 1998; Mursula et al., 2001) in favor of the simultaneous occurrence of Pc 1 pearls and ULF waves with period matching the pearl repetition period.

In view of the later discussion, let us still repeat some of the most obvious phenomenological differences between the BWP model and the

EGM/ULF model. One important feature in the BWP model is that pearl dispersion should increase fairly systematically during a pearl event because of the increasing path of the BWP. In the EGM models dispersion should not depict any clear trend but should remain more or less constant or slightly fluctuate randomly. In the BWP model, the pearl repetition time is obviously related to the wave bouncing time while in the EGM/ULF model it is related to the period of the modulating ULF wave. These can be tested occasionally even with satellite observations.

Finally, we would like to note that while heavy ions affect the wave propagation similarly in both models, the EGM/ULF model is slightly more dependent on the heavy ion content than the BWP model, partly by the possible heavy ion effect upon the modulating ULF waves, partly by the possibility that some properties of heavy ions (e.g., density) may be modulated and may cause related variations in EMIC wave growth rate.

4. Pc 1 pearl observations in upper ionosphere: pearl duration and dispersion

Despite the frequent occurrence of Pc 1 pearls on ground, there are only a rather small number of satellite observations of pearls. Individual EMIC wave packet series have reported, e.g., by Perraut (1982) close to equator by GEOS-2 satellite and by Erlandson et al. (1992) and Erlandson et al. (1996) in the mid-altitude magnetosphere by the Viking satellite. Iyemori and Hayashi (1989) observed a few short non-repetitive Pc 1 bursts in the ionospheric F-region by the Magsat satellite.

The infrequent occurrence of Pc 1 pearls, especially chains of repetitive Pc 1 pearls, in satellite observations remained long a puzzle. This puzzle was solved by the measurements of the low-altitude Freja satellite whose 600 km × 1750 km, 63°inclination orbit allows Pc 1 waves to be studied in the upper ionosphere with a good coverage of the plasmapause region. Mursula et al. (1994b) examined the global occurrence and spectral properties of Pc 1 waves by the Freja electric field instrument on November 18, 1992, when a long chain of Pc 1 pearls was observed on ground. In agreement with earlier studies, Pc 1 pearls were found to be related to the plasmapause. Also, in agreement with simultaneous ground observations, the satellite wave events were found to be located in a large part of the morning–noon sector, occurring for more than 10 h. Moreover, the Pc 1 source was observed to drift westward, i.e., in the ion drift direction.

During the 12-h period, due to the Earth's rotation, the apogee (perigee) of Freja orbit varied between 60°and 75°(resp., −53° to 78°) CGMlat. Accordingly, the satellite crossed the plasmapause latitudes at very different angles (and speeds). On the high-latitude orbits, Freja crossed the plasmapause more rapidly than on the low-latitude orbits where it was moving nearly longitudinally. This was seen as variable lengths of the observed Pc 1 pearls. However, the latitude range traversed by Freja during the Pc 1 events was roughly constant, about 0.5°CGMlat, yielding the first estimate of the latitudinal width of Pc 1 pearls in space. This width is so small that on high-latitude orbits Freja detected only a part of the full Pc 1 packet. This explains the rather rare observation of these waves in space, especially by polar, low-altitude satellites where Pc 1 bursts with very short durations of about 5–10 s (but no repetitive packets) have been observed (Iyemori and Hayashi, 1989).

Freja also detected one Pc 1 pearl with a full length (see Fig. 2) when travelling longitudinally at the plasmapause latitude. The full Pc 1 pearl lasted 25 s whence the satellite covered only 0.11°CGMlat. Since Freja did not see other wave activity in the remaining time of the 0.5° CGMlat latitude region, this proves that Pc 1 activity really consisted of separate pearls rather than continuous activity. The observed pearl duration of about 25 s is in a good agreement with a typical pearl length observed on ground, and with the results by Erlandson et al. (1992) where packet durations of 20–30 s were found in space. Moreover, from the overall "hit" probability of Pc 1 waves Mursula et al. (1994b) could conclude that the narrow Pc 1 shell was indeed active during all, or at least most of the 12-h time interval in the whole large MLT range (morning sector). The Freja event depicted in Fig. 2 was the first observation of a clearly dispersive Pc 1 pearl in space. The dispersion rate (change of frequency in time) was also in agreement with simultaneous ground pearls.

The good overall agreement between ground and Freja pearls suggests that Pc 1 pearl waves are indeed generated in the equatorial magnetosphere, and attain their dispersion while propagating from the equator to lower altitudes along the field line. (Note that there was no hint of wave reflection among the Freja Pc 1 events.) As noted above, the observation of Pc 1 pearls in space is complicated by

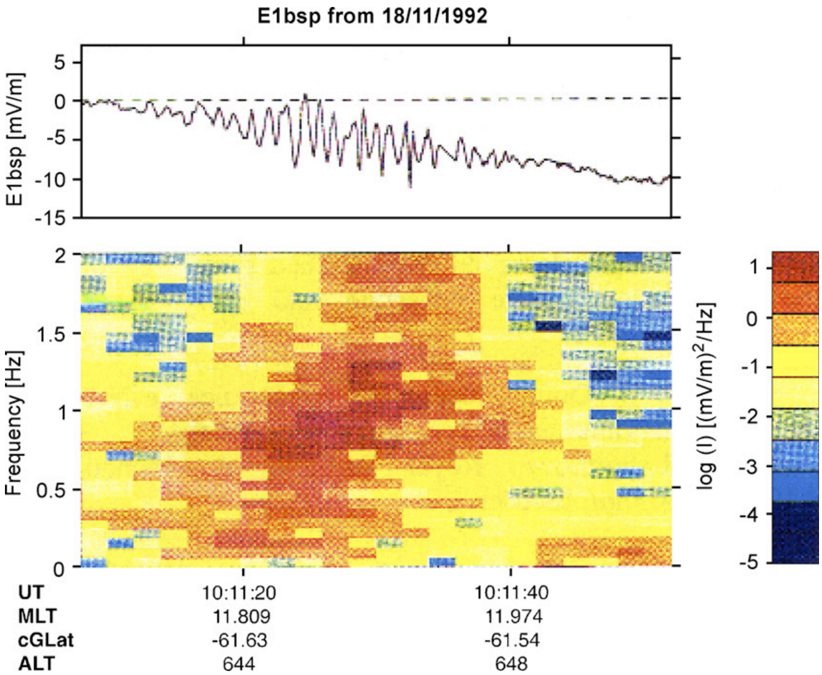

Fig. 2. Wave form and color coded spectral density of a dispersive Pc 1 pearl observed by the Freja electric field E1 component (magnetic field direction in spin plane) in November 18, 1992 (Mursula et al., 1994b).

the very narrow latitude range of wave occurrence. This narrowness may be, at least partly, due to field-aligned wave guiding which is greatly facilitated by density gradients (Mazur and Potapov, 1983; Thorne and Horne, 1992).

5. Pc 1 pearl observations at high altitudes: pearl repetition rate and Poynting flux

As discussed above, a low-altitude satellite like Freja traverses latitudes too fast to detect more than one packet during one crossing of the narrow Pc 1 active region. Accordingly, these observations cannot give information on pearl repetition period or the possible change in dispersion during a pearl necklace. However, satellites with apogee at higher altitudes may, at least occasionally, stay longer in this region to detect several Pc 1 packets. Erlandson et al. (1992) and Erlandson et al. (1996) studied a Pc 1 event consisting of several wave packets observed at mid-altitudes by the Viking satellite. Both studies detected similar repetition periods at Viking and on ground, contrary to the BWP model. They concluded that the reflected wave power, if existing at all, must be much smaller than that heading toward the ionosphere.

In another Viking satellite study, Mursula et al. (1997) found two separate Pc 1 wave regions with slightly different frequencies (0.3 and 0.5 Hz) at neighboring L shells just outside the plasmapause (around $L = 6$). The latitudinal extent of both wave regions was about 0.5°. The two waves had also slightly different normalized frequencies, Alfvén velocities, and repetition periods. Most interestingly, the repetition periods of both wave sources (about 40–45 s) were too short for bursts to be due to a wave packet bouncing between the two hemispheres. On ground, a persistent Pc 1 chorus event was observed with frequency range covering both Viking bands, indicating that these high-latitude Pc 1 waves may also consist of separate repetitive (but nonbouncing) bursts from several incoherent sources.

It was subsequently shown (Rasinkangas and Mursula, 1998) that, before and during the Viking Pc 1 event, persistent ULF waves of closely similar frequency (about 42 s) were seen in the upstream region, at the geosynchronous and mid-altitude magnetosphere, and on ground at several stations. These waves seemed to permeate most of the dayside magnetosphere by the time of Viking observation of Pc 1 bursts. The ULF frequency match with the repetition period of Viking Pc 1 packets suggests that upstream waves can leak into the inner magnetosphere (probably via conversion to magnetosonic waves), and modulate the Pc 1 wave growth rate. The event suggests that EMIC wave modulation by ULF waves is a fairly general phenomenon in the magnetosphere concerning also other morphological types of Pc 1 waves than pearls.

The observational conditions were exceptionally favorable on April 25, 1997, when a strong Pc 1 pearl event was observed by the Finnish search-coil magnetometer network and by the electric and magnetic field instruments on board the Polar satellite in an excellent conjunction (Mursula et al., 2001). Polar observed two wave bands, inside, at and slightly outside of the plasmapause. The low-frequency He^{+}-band waves consisted of three repetitive bursts which were observed on ground as a strong, classical Pc 1 pearl band. The same repetition period of about 100 s was found for the Polar He^{+}-band bursts and ground Pc 1 pearls (see Fig. 3), in conflict with the BWP model. Comparing the burst structure of He^{+}-band waves in Polar and on ground (see Fig. 3), a transit time of about 43 s and an average group velocity of about 500 km/s were found between Polar and ground. In the BWP model, this velocity would lead to a pearl repetition period of more than 250 s, in dramatic contradiction with the observed repetition period.

Ample evidence was found for the ULF modulation of Pc 1 pearls. The Pc 1 pearl waves were accompanied at Polar by long-period ULF waves which had a period matching with the repetition period of pearls. All the stations of the IMAGE ground magnetometer network close to the satellite footpoint also depicted considerable power at the same ULF frequency (see Fig. 4). The agreement was so good that the closest conjugate stations (Oulujärvi, OUJ) depicted the strongest peak and the best frequency match with the Polar ULF frequency. Also, plasma density at Polar showed simultaneous fluctuations with roughly the same period as ULF waves. This suggests that the ULF waves can indeed modulate the relevant plasma parameters and, thereby, affect the EMIC wave growth.

Polar was the first satellite which was able to measure the complete three-component electric and magnetic fields. This made it possible to determine the full Poynting vector of the Pc 1 waves in space for the first time (see Fig. 5). The magnitude of the total Poynting flux of the He^{+}-band waves was about 20–25 mW/m^2. Most interestingly, the Poynting vector was strongly directed downward away from the equator, thus excluding any significant power for waves reflected

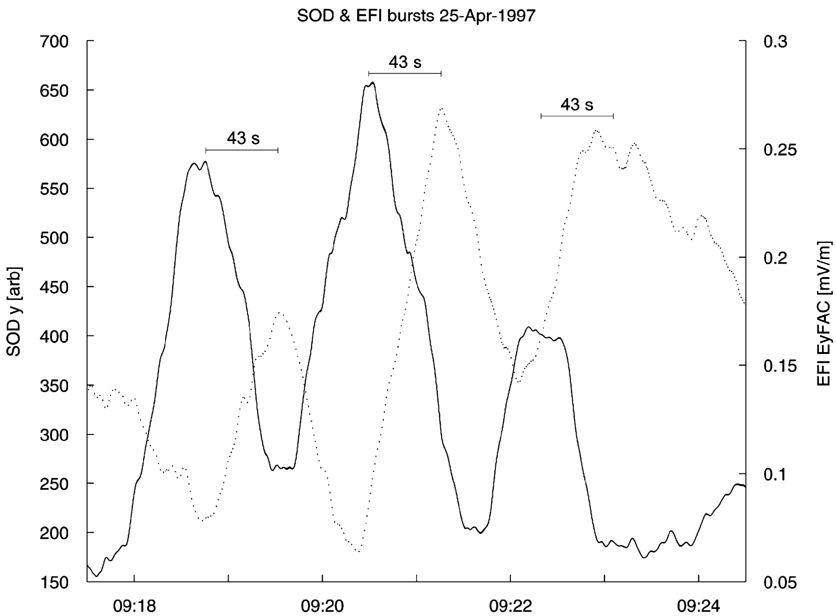

Fig. 3. Envelope curve of the amplitude of the filtered signal (0.8–1.2 Hz) of the Polar He^{+}-band EMIC wave bursts (solid line) and of the Pc 1 pearls observed at SOD (dotted line) in April 25, 1997, at about 0920 UT (Mursula et al., 2001).

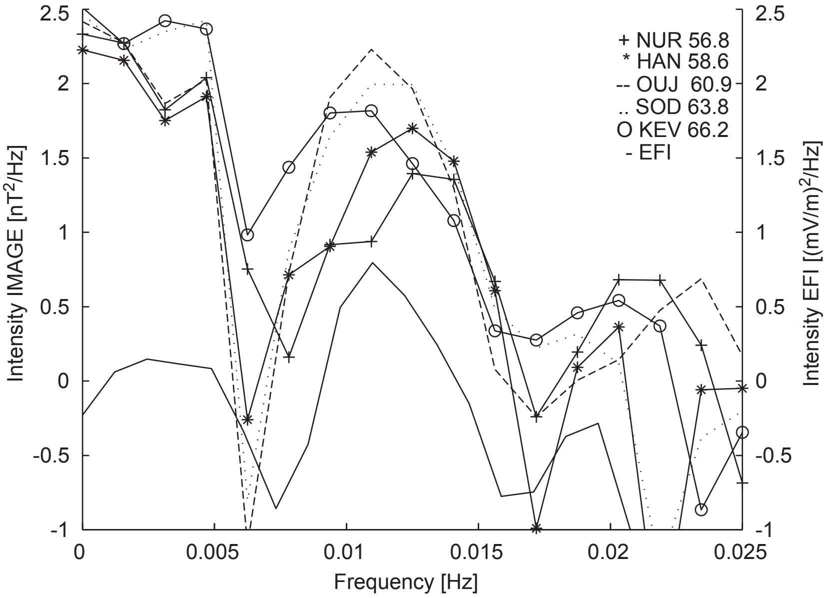

Fig. 4. Power spectra of Polar electric field (EFI) FAC *x*-component (solid line) and of the *H*-component of several Finnish IMAGE magnetometer stations in April 25, 1997, at about 0920 UT (Mursula et al., 2001). Dipole latitudes of each station are noted.

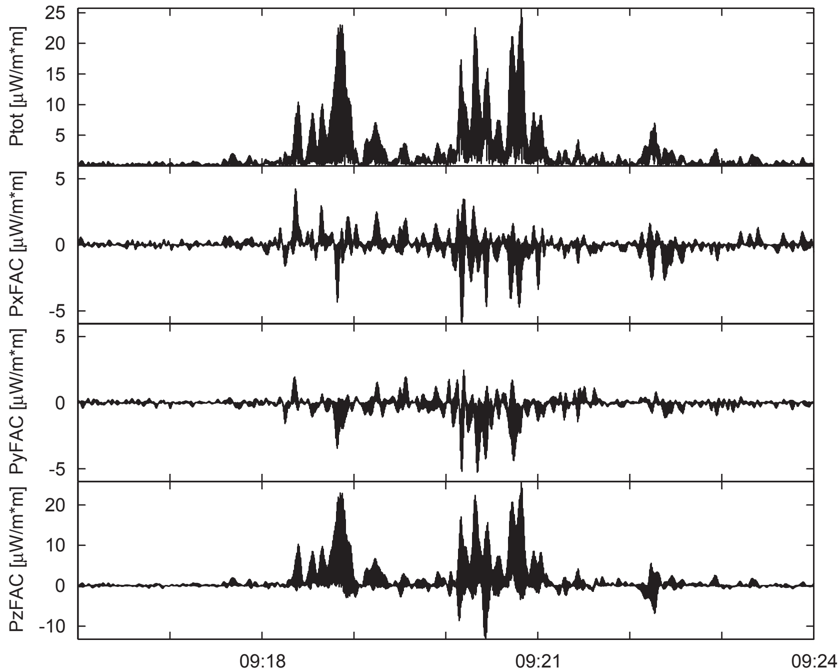

Fig. 5. The total Poynting flux (top) of the Polar He^{+}-band EMIC waves and its three (*x*, *y*, *z*) FAC components. The flux values are given in units of $\mu W/m^2$ (Mursula et al., 2001).

from the ionosphere. The Poynting vector also had a small eastward component, possibly related to the westward drift of the energetic ions producing the EMIC waves. These detailed results (Mursula et al., 2001) reject the BWP model as the cause of Pc 1 pearls and, instead, favor the

EGM/ULF model as a viable scenario for Pc 1 pearl formation.

The propagation direction of EMIC waves has been examined in a number of satellite studies. E.g., Loto'aniu et al. (2005) observed nearly 300 EMIC wave events using CRRES satellite measurements, and calculated their Poynting vectors. Although the Poynting vectors were not complete because not all field components were available, the results are quite conclusive. They found that outside of a narrow region of about $\pm 11^\circ$ Mlat around the equator, the Poynting vectors were systematically directed away from the equator along the magnetic field (see Fig. 6). Accordingly, while the narrow equatorial growth region depicts interesting wave dynamics, the CRRES observations give a very strict limit (of at most a few per mille only) upon the relative number of such EMIC wave packets that are reflected back from either ionosphere and are sufficiently strong to be detected by the satellite close to the equator (and to modify the equatorial plasma parameters affecting EMIC wave growth).

In another fortunate case event on May 7, 1998, the Polar satellite traversed across the Pc 1 active latitude so slowly that it observed a long chain of Pc 1 pearls in space. Fig. 7 depicts the dynamic spectrum of the observed He^+-band waves consisting of some 10 Pc 1 bursts (Mursula et al., 2007). The event was detected quite deep in the magnetosphere at about $L = 3.5$, in the pre-noon MLT sector. It is notable that there is no evidence for a systematic increase of dispersion during the event. Even in this case, simultaneous ULF waves with

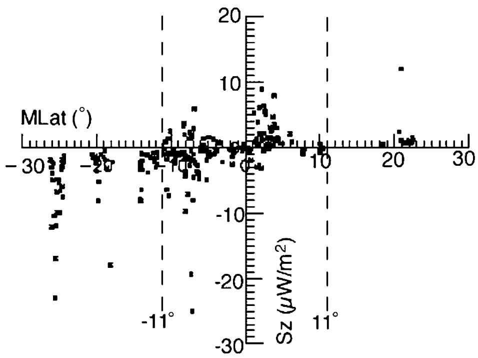

Fig. 6. The field-aligned Poynting vector (Sz, vertical axis) versus Mlat for 248 EMIC events observed by the CRRES around the equator. The dotted vertical lines indicate the $\pm 11^\circ$ Mlat locations beyond which all waves propagate away from the equator, being positive above equator and negative below equator (Loto'aniu et al., 2005).

period close to Pc 1 pearl repetition period were observed at Polar.

We would also like to mention a new class of rare EMIC events whose bursts contain an exceptionally large frequency range (Mursula et al., 2007). Fig. 8 depicts such an event consisting of two bursts whose frequency range is more than 1 Hz, i.e., some 3–5 times larger than in a regular Pc 1 pearl band. The bursts depicted in Fig. 8 were seen to rise from a pre-existing series of He^+-band EMIC waves at $L = 5$ on April 23, 1997. Although such bursts are not directly related with Pc 1 pearls, they can still be used to study models of packet formation. If these repetitive bursts with an exceptionally large frequency range were due to one BWP, they should depict changing dispersion. Taking into account the large frequency range of these bursts, one would expect the change of dispersion to be visible even between two successive wave packets. However, as seen in Fig. 8, there is no change in dispersion between the two bursts. Accordingly, these bursts are not due to one BWP. Such bursts with an exceptionally large frequency range may be due, e.g., to solar wind pressure pulses that are known to generate Pc 1 waves (Olson and Lee, 1983; Kangas et al., 1986; Mandt and Lee, 1991). This interpretation is supported by the fact that the event occurred almost exactly at noon.

6. Conclusions

We have discussed here a few important ground-based and, in particular, satellite-based observations of Pc 1 pearls, and two models aiming to explain the packet structure. We noted that the bouncing wave packet model is based on an intuitive and suggestive analogue with VLF whistlers which, however, does not hold good in a more detailed analysis, and on ground-based evidence which is largely out-of-date and questionable, if not completely invalid. On the other hand, we have shown that a multitude of both ground-based and, in particular, satellite observations favor the alternative model of Pc 1 packet formation, the modulation of equatorial EMIC wave growth by ULF waves.

By now, a few events of individual dispersive Pc 1 pearls and even Pc 1 pearl series (necklaces; Sucksdorff, 1936) have been detected in space at different locations, ranging from the upper ionosphere to the near-equatorial magnetosphere. These studies have shown that coherent EMIC waves such

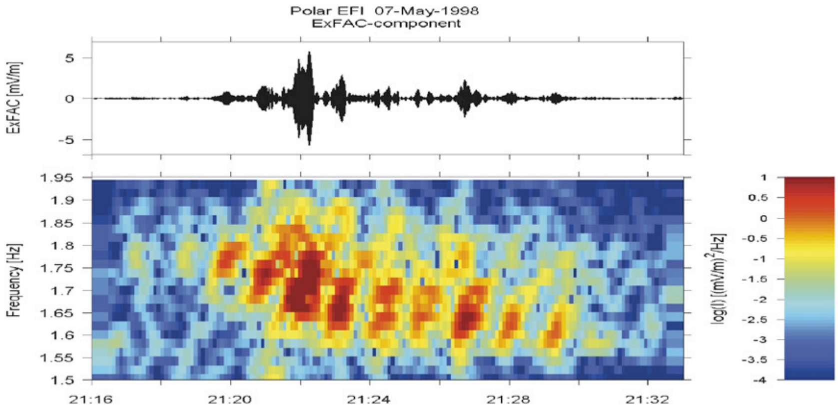

Fig. 7. Waveform and spectrogram of Polar electric field (x FAC-component) on May 7, 1998. The data are band-pass filtered over the wave frequency range at 1.5–2.0 Hz.

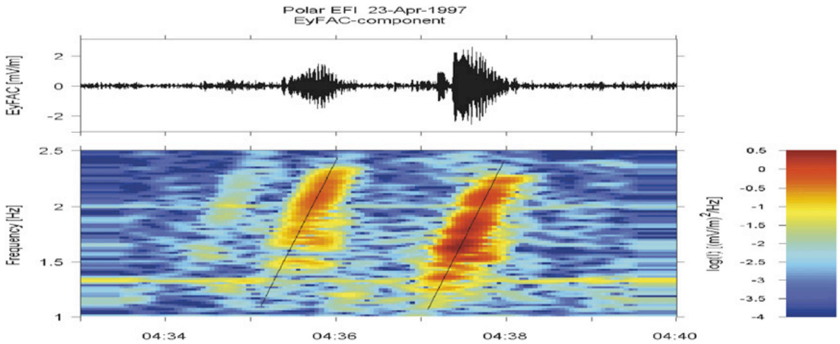

Fig. 8. Waveform and spectrogram of Polar electric field (x FAC-component) on April 23, 1997. The data are band-pass filtered over the wave frequency range at 1.0–2.5 Hz. The inclined lines are best fits to spectra in order to better depict the overall dispersion.

as Pc 1 pearls are limited to a rather narrow latitudinal range of about 0.5° of invariant magnetic latitude, which explains their rare observation in space. In a few satellite studies, the observed pearl repetition period was conclusively verified to be too short to be explained by the bouncing wave packet model. On the other hand, in all satellite studies where the repetition period of Pc 1 pearls could be determined, simultaneous ULF waves were found to exist with period coinciding with pearl repetition period.

We noted that, contrary to a common misconception, Pc 1 pearls observed on ground do not depict a systematic increase of dispersion during a pearl chain. The same is true for satellite observations of Pc 1 pearl events: there is no evidence for a systematic increase of dispersion within a pearl series, or in other types of repetitive EMIC wave bursts. Rather, dispersion remains roughly similar or fluctuates randomly even in long pearl series both on ground and in space.

The complete Poynting vector of EMIC waves has been determined for a few Pc 1 pearls and found to be dominated by the field-aligned, downward directed component. Large statistical survey shows conclusively that the number of detectable wave packets reflected from the ionosphere is insignificantly small.

Accordingly, all facts obtained from satellite studies are in agreement with the EGM/ULF modulation model of Pc1 pearls, while many studies are in a strong disagreement with the bouncing wave packet model. Thus, we must conclude that the model of a bouncing Pc 1 wave packet, or anything similar to that, must be rejected as a paradigm model to explain Pc 1 pearl structure. Instead, the equatorial modulation of Pc 1 growth rate by ULF waves, being in agreement with all ground-based and space observations, deserves to be considered the paradigm model henceforth.

Note that the relative importance of in-phase versus out-of-phase modulation of pearl packets in the conjugate ionospheres (and the related question of the dominant ULF wave mode) is not straightforward in EGM/ULF modulation model since, on one hand, ion cyclotron instability should be more efficient during in-phase modulation (symmetric ULF wave) but, on the other hand, out-of-phase modulation (asymmetric ULF wave) might increase the time spent in the generation/amplification region, increasing the convective growth rate. This suggests a need for more detailed observations of Pc 1 pearls and ULF waves in conjugate locations, and for multi-point satellite studies close to the equatorial growth region. Moreover, related theoretical studies are required in order to better understand the physics of modulation for different types of ULF waves.

Finally, we would like to note that the well-known occurrence of Pc 1 pearls at the plasmapause is naturally understood in the EGM/ULF model since the large density gradients in the plasmapause region enhance the effect of ULF waves upon the density (and indirectly upon other plasma parameters) and thereby upon the EMIC growth rate. Also, the conversion of externally driven (e.g., solar wind pressure pulse related) compressional waves to other ULF wave modes takes place more effectively in the plasmapause region, explaining naturally why the external disturbances often lead to Pc 1 pearl generation, especially in the dayside. Thus in the EGM/ULF model there is a natural connection between the source location of Pc 1 pearls and the plasmapause. No similar connection exists in the BWP model, although in both models large plasma gradients around the plasmapause may facilitate wave propagation.

Acknowledgments

I thank Jorma Kangas for an invitation to present a review talk at the Session ST4.6 of EGU General Assembly, 2006. I also thank the two unknown referees for knowledgeable and interesting comments, and the editors of this Special issue for phenomenal patience while waiting for the preparation of this review.

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