Earth and Planetary Science

https://journals.nasspublishing.com/index.php/eps

RESEARCH ARTICLE

ULF Pulsations as a Driver of Relativistic Electrons: Pros and Cons

Vyacheslav Pilipenko [1,2*], ***Olga Kozyreva*** [2], ***Vladimir Belakhovsky*** [3,4]

[1] *Plasma Physics Department, Space Research Institute, Moscow 117997, Russia*

[2] *Laboratory of Near-Earth Environment, Institute of Physics of the Earth, Moscow 123242, Russia*

[3] *Auroral Phenomena Laboratory, Polar Geophysical Institute, Apatity 184209, Russia*

[4] *Institute of Solar-Terrestrial Physics, Irkutsk 664033, Russia*

ABSTRACT

Ultralow frequency (ULF) waves in the Pc5 band have been suggested as a possible intermediary transferring energy from high-speed streams of the solar wind to magnetospheric electrons. Although ULF waves are not the only mechanism of accelerating electrons up to relativistic energies, nonetheless they are an essential element of the electron energization process, though their role has not been finally established yet. Among observational facts regarding the interrelationships between Pc5 wave activity and electron dynamics, we discuss the following pro and con factors related to the ULF-associated energization mechanisms: The correlation of electron fluxes at the geostationary orbit and the Pc5 wave power; The correspondence between the azimuthal phase velocities of toroidal and poloidal Pc5 waves and the electron magnetic drift; The correspondence between the latitudinal structure of Pc5 waves and the outer radiation belt. Consideration of these facts does not allow one to unambiguously resolve the issues concerning the role of ULF waves in the magnetospheric electron energization. We suggest that the acceleration of electrons by ULF disturbances may occur not in a regime of "geoserfotron" with Pc5 waves (match of the azimuthal velocities of waves and drifting electrons), but rather in a regime of "geosynchrotron" with transit-time acceleration by substorm-related Pi3 pulsations.

Keywords: Outer Radiation Belt; Relativistic Electrons; Auroral Oval; ULF Pulsations

*CORRESPONDING AUTHOR:

Vyacheslav Pilipenko, Plasma Physics Department, Space Research Institute, Moscow 117997, Russia; Laboratory of Near-Earth Environment, Institute of Physics of the Earth, Moscow 123242, Russia; Email: space.soliton@gmail.com

ARTICLE INFO

Received: 23 October 2024 | Revised: 13 January 2025 | Accepted: 8 February 2025 | Published Online: 13 March 2025

DOI: https://doi.org/10.36956/eps.v4i1.1310

CITATION

Pilipenko, V., Kozyreva, O., Belakhovsky, V., 2025. ULF Pulsations as a Driver of Relativistic Electrons: Pros and Cons. Earth and Planetary Science. 4(1): 1–9. DOI: https://doi.org/10.36956/eps.v4i1.1310

1. Introduction

1.1. ULF Waves as Driver of "Killer" Electrons

The global electrodynamics of the near-earth space is driven by the solar wind (SW) and interplanetary magnetic field (IMF). However, many processes develop entirely inside the magnetosphere, because in a collisionless space plasma the SW flow does not interact directly with magnetospheric particle population. Among them is the acceleration of magnetospheric electrons to relativistic energies in the outer radiation belt. Understanding the physical nature and prediction of the radiation belt response to interplanetary driving is still a challenge for space physicists. Moreover, the "killer" electron events are not merely a scientific curiosity, but they can have disruptive consequences for spacecraft electronics [1]. The SW relativistic electrons cannot be a source of magnetospheric relativistic electrons because their phase space density is too low to feed the observed increases of electron fluxes in the inner magnetosphere [2]. Therefore, the outer radiation belt formation is due to some internal magnetospheric process where electromagnetic fields play a role of intermediary transferring the energy from lower energy seed particles to a small group of high-energy electrons. There are, possibly, a variety of mechanisms of magnetospheric electron acceleration up to relativistic energies, and depending on geophysical situation, some acceleration mechanisms prevail.

The dynamics of the outer radiation belt is determined by a complicated action of various energization, transport, and loss mechanisms. Rapid increase of high-energy particle fluxes in the magnetosphere 20–40 min after a solar flare suggests that interplanetary shock is an efficient accelerator of electrons up to 6 MeV [3, 4]. The magnetic storm main phase is typically accompanied by a dropout in the outer electron belt flux which is attributed to adiabatic decrease during the magnetosphere compression and loss due to magnetopause shadowing. A dropout is followed by rebuilding during the storm recovery phase when the electron fluxes are adiabatically restored to their pre-storm values. However, in ∼50% of storms the electron enhancements go well beyond the adiabatic level. These enhancements stem in two phases. First, the embryo of the relativistic electron flux intensification occurs in the heart of the belt ($L\sim$3–4) and on rapid time scales (about several hours), and later and more slowly (days to weeks) at higher altitudes [5–8].

The fast acceleration phase is seemingly related to the substorm growth. The amount of energy contained in the outer belt MeV electrons is smaller than that released in a typical substorm by orders of magnitude, thus only a small fraction of the substorm energy is needed to feed the radiation belt electrons. Rebuilding of ∼1 MeV electrons is due to a considerable extent to injections from the nightside magnetosphere, though it is not known to what degree the transport from the plasma sheet is sufficient to produce radiation belt enhancements. While some studies suggested that substorm dipolarization and associated energization alone are sufficient to account for observed radiation belt enhancements [9–11], others claimed that it is necessary to include additional acceleration mechanisms. For example, Kim et al. [12] modeled in 3D MHD simulations the substorm-associated acceleration of energetic (tens of keV) plasma sheet electrons upon their injection into the outer-trapped region of the magnetosphere and concluded that via betatron acceleration they can gain about order of magnitude in energy. But, to have energies of an MeV these particles are to be further transported inward to L∼6 by some mechanism. Estimation of the number of accelerated electrons indicated that moderate substorm produces only several % of the number of MeV electrons observed in a typical post-storm outer belt enhancement.

There have been evidence indicating the ultra-low-frequency (ULF) wave contribution to the later slower energization phase [13, 14]. The time delay ∼2–3 days of the peak values of electron fluxes after storm onset at geosynchronous orbit inspired the idea of gradual diffusion-type acceleration caused by ULF activity [15]. The radial transport due to magnetospheric ULF oscillations during storm recovery transports the newly trapped electrons earthward and energizes them due to betatron acceleration [16]. The resonant interaction of drifting electrons with Alfven oscillations in the Pc5 frequency band can be a magnetospheric intermediary providing the energy to the electrons [17–19]. This acceleration mechanism requires seed electrons of a few hundred keV which are supplied by substorms.

On the other hand, observations and theoretical models indicated that very-low-frequency (VLF) emissions (1–10 kHz) can play a key role in the acceleration of magnetospheric electrons [20]. Such VLF radiation turned out to be "chorus" - narrow-band emissions with a strong frequency dispersion, excited by energetic electrons [21]. The effects of VLF electron acceleration dominate over their pitch-angle scattering into a loss cone at a sufficiently high initial electron energy. Numerical modeling predicted that under intense chorus emission in the inner magnetosphere the electron flux can exceed the average flux in the heart of the outer radiation belt in $\sim$1 day [22].

Some earlier theories of the outer radiation belt formation were based on the mechanism of radial particle diffusion caused by inductive electric fields excited upon permanent buffeting of the magnetosphere by SW impulses [23]. Nowadays, the conception of a faster process - resonant interaction of $\sim$100 keV seed electrons supplied by substorms with ULF waves, becomes more popular. The period of the electron drift with energy *W* and pitch-angle at *L*-shell can be estimated from the Equation (1)

$$T_d \simeq \frac{44}{LW\,[MeV]}(0.7 + 0.3\,sin\alpha) \quad (1)$$

According to this relationship at L = 5 for 1-MeV electrons $T_d \sim 6$ min, whereas for 100-keV electrons $T_d \sim 1$ h. The drift resonance between drifting electron and azimuthally propagating waves with the wave number *m* occurs when the azimuthal phase velocity matches the electron angular velocity $\omega_d = 2\pi/T_d$ as shown in Equation (2) [24–26]

$$\omega/m = \omega_d \quad (2)$$

The resonant condition in Equation (2) means that waves must propagate in the same azimuthal direction as electrons, and with the same phase velocity as the electron drift. This mechanism resembles the particle acceleration at the front of propagating electromagnetic wave [27] and may be coined the "geoserfotron" mechanism.

The mechanism was suggested that did not require any ULF or VLF activity for the electron energization [28, 29]. According to this scenario, first an injection of energetic electrons into a region with a depressed by the ring current magnetic field occurs, then upon a recovery of magnetospheric magnetic field their energy increases due to betatron acceleration [30]. For a steep energy spectrum even a relatively weak enhancement of the magnetic field should lead to a considerable increase of fluxes.

A high substorm activity on recovery phase is probably a necessary attribute of a significant enhancement of relativistic electrons after a storm. Tverskaya et al. [31] found many storm events with $|\text{Dst}|_{max}$ = 65–237 nT and high-speed SW (V_{sw} > 500 km/s), but no afterstorm enhancement of relativistic electrons. All these cases were associated with low substorm activity during the recovery phase. At the same time many moderate storms with $|\text{Dst}|_{max}$ = 30–100 nT and low V_{sw} < 450 km/s with large (order of magnitude) enhancement of relativistic electron intensity exhibited a high substorm activity on the recovery phase. The mechanism of this relationship is not clear yet, possibly high substorm activity at the storm recovery phase stimulates a higher level of ULF/VLF activity and seed electron fluxes.

1.2. Long-Period Disturbances in the Magnetosphere

ULF waves are a persistent component of a disturbed magnetosphere. During storms different classes of ULF activity can be observed:

Toroidal Alfven waves (period T is about several mins) are azimuthally large-scale (that is with small azimuthal wave numbers m) quasi-monochromatic oscillations. They are incompressible field line oscillations polarized in the azimuthal direction, so their dominating components in the magnetosphere are azimuthal magnetic $B_\phi >> B_r$, and radial electric $E_r >> E_\phi$, whereas the compressional magnetic component vanishes, $B_\parallel \sim 0$. Thus, only relatively weak component E_ϕ provides the energy exchange with azimuthally drifting electrons. The narrow latitudinal localization (width

$\sim$1–2°) of toroidal Pc5 waves is caused by Alfven field-line resonance. The main source of Pc5 toroidal pulsations is the Kelvin-Helmholtz instability of the magnetopause engulfed by the SW flow, so Pc5 intensity grows statistically with the increase of the SW velocity. Pc5 waves are predominantly observed at auroral latitudes at morning LT hours. Sudden jumps of the SW pressure may be an additional source of transient Pc5 oscillations throughout the dayside magnetosphere.

Poloidal Alfven waves (storm-time Pc5 pulsations) are field line oscillations polarized in the radial direction, so the dominating components are radial magnetic $B_r >> B_\phi$ and azimuthal electric $E_\phi >> E_r$. These waves are commonly coupled with slow compressional mode, so they have a significant compressional component $B_\| \sim B_r$. Thus, these waves can effectively exchange energy with azimuthally drifting particles. These waves reveal clearly small-scale periodic structure in azimuthal direction, that is large $m\sim$30–100. Poloidal pulsations in the Pc5 frequency band can be resonantly excited by fluxes of energetic ring current protons with a non-Maxwellian distribution in energy (bump-in-tail instability) or with a steep pressure gradient (drift instability). Because of their small-scale in the direction across the geomagnetic field, they are nearly totally screened by the ionosphere from ground magnetometers.

Waveguide mode (global Pc5 waves). The most intense Pc5 waves, with amplitudes exceeding by an order of magnitude those of common Pc5 pulsations, are observed during the recovery phase of severe magnetic storms under high-speed SW streams [32]. These anomalously strong pulsations are referred to as global Pc5 pulsations [33] because they are observed simultaneously in the morning and evening sectors over a wide range of latitudes. Their dominating components in the magnetosphere are B_r and E_ϕ. Global Pc5 pulsations occur when the energy flux from the SW due to the reconnection is suppressed and they become a significant channel of the wave energy transfer into the magnetosphere. Global Pc5 waves can be interpreted as a waveguide fast-magnetosonic mode, established between the magnetopause and reflection point deep in the inner magnetosphere [34]. Apart from exceptionally high amplitudes, global Pc5 pulsations, associated with the magnetospheric waveguide mode, decay from auroral to low latitudes much more gradually than common Pc5 pulsations and penetrate deeper into the inner magnetosphere. However, global Pc5 pulsations are excited under exceptional conditions and are relatively rare.

Pi3 pulsations are a quasi-periodic sequence of intense (up to several hundred nT) impulses (with time scale 5–20 min) and constitute a fine structure of magnetospheric substorm. The power of Pi3 pulsations is spatially concentrated in the region of the auroral electrojet [35]. Quasi-period of Pi3 is much larger than Alfven fundamental eigenperiod at auroral latitudes, so these pulsations, in contrast to Pc5 waves, cannot be interpreted as Alfven field line oscillations. Excitation mechanisms of Pi3 pulsation is probably associated with dynamics of bursty processes in the magnetotail, but it has not been established yet.

During magnetic storms all possible drivers of magnetospheric ULF pulsations are to be strongly activated, so any of the above ULF waves may be considered as potential energy reservoir for relativistic electrons. In principle, a combination of several mechanisms can operate. For example, a radial transport and pre-energization of electrons driven by ULF waves may be augmented by local acceleration by VLF emissions. Further, we consider arguments in favor and against the energization mechanism by different types of ULF Pc5 waves.

2. Pro: Statistical Relationships between the ULF Activity and Relativistic Electrons at the Geosynchronous Orbit

The long duration elevated Pc5 wave power during the recovery phase appeared to discriminate better than any geomagnetic indices between those storms that do and do not produce relativistic electrons. The main phase intensity characterized by Dst index did not appear to be an important indicator of subsequent electron response [36]. As a measure characterizing the level of the ULF power in the magnetosphere, the hourly ULF index has been used [37]. This wave power index characterizes the ground ULF activity in frequency band from 1.7

mHz to 8 mHz on a global scale and is calculated from a world-wide magnetometer array. A long-term persistent ULF activity was found to be more important for electron acceleration than short-term, though intense, ULF bursts [38]. Comparison between Dst index, electron fluxes at the geosynchronous orbit, and cumulative ULF index showed that there was no simple correspondence between the magnetic storm intensity and magnitude of electron enhancement. Sometimes, the sustained intense increase of the relativistic electrons fluxes was observed after a weak storm (|Dst| < 100 nT), whereas the increase after a strong storm (|Dst| > 200 nT) was much shorter and less intense. The electron behavior matches well the variations of the ULF-index, so the cumulative ULF index characterizes the electron dynamics much better than Dst index. The elevated level of cumulative ULF wave activity precedes the peak of relativistic electron flux for about 1 day, which implies the occurrence of a cumulative effect of some diffusion process.

To determine a physical mechanism of the magnetospheric electron acceleration to relativistic energies it is necessary to identify the region of electron energization and its possible drivers in the context of structure of the magnetosphere. During magnetic storms both the outer radiation belt and all magnetospheric domains are very dynamic, so any empirical statistical models cannot help much. Magnetospheric domain which might be important for electron dynamics is the auroral oval [39]. This magnetospheric domain with intense field-aligned currents, high turbulence in wide frequency/spatial scales, essential distortions of the magnetic field geometry, and high fluxes of seed auroral electrons, is also filled with intense Pc5 waves [40]. These waves may provide an enhanced radial transport inward the magnetosphere and acceleration of electrons.

The above consideration is a strong argument in favor of Pc5 waves as energization mechanism of magnetospheric electrons. However, such measure of ULF activity as band-integrated spectral power cannot discriminate between the quasi-monochromatic Pc5 waves and irregular Pi3 pulsations in the same frequency band. Therefore, all the facts evidencing the important role of ULF in electron dynamics support both Pc5 and Pi3 activity as possible electron drivers.

3. Con: Azimuthal Propagation of Pc5 Waves and Magnetospheric Electrons

The resonant condition (2) indicates that for an effective transfer of energy from waves to particles waves must propagate in the same azimuthal direction as electrons, and with the same phase velocity as electron drift. How does this condition is fulfilled for toroidal, poloidal, and waveguide Pc5 pulsations? The existing information is summarized and illustrated in **Figure 1**.

The comparison of wave signatures from longitudinally separated ground magnetometers has shown that toroidal Pc5 pulsations propagate westward (antisunward) both in the morning and afternoon sectors. Similarly, global Pc5 waves also propagate westward both during morning and afternoon hours, though with somewhat different phase velocities. Such westward wave propagation pattern makes the drift resonance described by Equation (2) with eastward drifting energetic electrons impossible. Moreover, the needed component E_ϕ is weak in the toroidal mode. Therefore, the possibility of electron energization up to relativistic energies by toroidal or global Pc5 waves seems questionable.

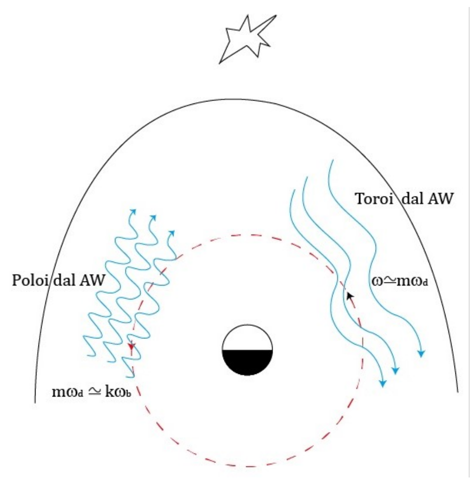

Figure 1. A sketch of possible resonant interaction between electrons and toroidal and poloidal Alfven waves (AW). Dashed line denotes the drift trajectory of electrons.

Do poloidal Pc5 waves contribute to post-storm electron energization? The effective exchange of energy between ULF waves and particles occurs under the drift-bounce resonance condition

$$\omega - m\omega_d - K\omega_b = 0$$

where ω_d is the bounce averaged angular drift velocity and K is the bounce harmonic number (the case $K = 0$ corresponds to the drift resonance). The idea that poloidal ULF waves with $m >> 1$ can effectively energize radiation belt electrons, on the time scale of a few hours, was promoted in many studies [41, 42]. However, poloidal Pc5 pulsations are most probably generated by energetic protons injected into the magnetosphere, so they propagate in the direction of proton drift, that is opposite to the electron drift. They hardly can resonantly interact with electrons, despite their favorable polarization with dominant component E_ϕ.

Another difficulty to apply Pc5-driven diffusion/energization mechanism to electron dynamics is the mismatch of their typical latitudinal distribution: electron energization starts in the middle magnetosphere (L∼3–4) and then expands to higher latitudes (L∼6–7), whereas typical Pc5 waves are strongly localized at sub-auroral latitudes and hardly can be detected at middle latitudes. Only global Pc5 waves during strong magnetic storms can penetrate to low latitudes [34] .

4. Possible Role of Pi3 Pulsations

The band-integrated ULF wave power cannot discriminate between quasi-monochromatic Pc5 waves and irregular quasi-periodic Pi3 pulsations. Thus, a high correlation between ULF power and electron dynamics could be performed to a considerable extent by Pi3 pulsations. The transit time of drifting electron across the small-scale Pi3 structure is much less the Pi3 periodicity, so they can be considered a quasi-steady structure with intense azimuthal electric field E_ϕ. Now we consider what kind of influence may be exerted on the energetic drifting electrons from azimuthally localized Pi3-type disturbances. For simplicity herein we only consider the particles mirroring near the geomagnetic equator. The energy imparted to the charged particle in a time-varying field can be estimated from the well-known formula

$$\delta W = \int dt \left(eV_d E_\phi + \mu \frac{\partial B_\parallel}{\partial t} \right) \quad (3)$$

Here e is the particle charge, $\mu = mV_\perp^2/2B$ is the particle magnetic moment, V_d is the electron azimuthal drift velocity, and integration is made along particle trajectories. We consider the particle acceleration induced by an azimuthally localized disturbance, such as

$$\left(E_\phi, B_\parallel\right) \propto exp\left[-(\phi/\Delta\phi)^2 - i\omega t\right] \quad (4)$$

where $\Delta\phi$ stands for the azimuthal extent of Pi3 source. We expand the wave fields into Fourier integral over time t and azimuthal angle ϕ, then for particles drifting along trajectories $\phi\,(t) = \phi_0 + \omega_d t$, where ϕ_0 is the initial particle phase, the energy gain per one pass through the disturbed region will be

$$\delta W = \int_{-\infty}^{\infty} dm \delta W_m$$

$$\delta W_m = \int dt \left[eV_d E_\phi\,(m,\omega) - i\mu\omega B_\parallel\,(m,\omega)\right] exp\left[-i\,(\omega - m\omega_d)\,t + im\phi_0\right]$$

Here m is the parameter of the Fourier decomposition (or wave number) in the azimuthal direction. Remembering that $\int_{-\infty}^{\infty} dt' exp\left(-i\alpha t'\right) = \delta\,(\alpha)$, we obtain

$$\delta W = \int dm \left[eV_d E_\phi\,(m,\omega) - i\mu\omega B_\parallel\,(m,\omega)\right] \delta\,(\omega - m\omega_d)\, exp\,(im\phi_0) \quad (5)$$

The resonance condition $\omega = m\omega_d$ in Equation (5) means that an energy transfer from the wave to the particles occurs only when the period of the wave $T = 2\pi/\omega$ is equal to particle drift period $T_d = 2\pi/\omega_d$ or its multiples. The factor $exp\,(im\phi_0)$ relates to the proper phasing between the particles and the oscillating field: depending on the initial phase some particles give energy to the wave, while others extract energy from it. Further we will consider Equation (5) averaged over group of particles with such phases that $\delta W \geq 0$. For such disturbance we have equations from (4) and (5)

$$\delta W = \frac{\sqrt{\pi}\Delta\phi}{\omega_d}\left[eV_d E_\phi - i\omega\mu B_\parallel\right] exp\left[-\left(\frac{\omega\Delta\phi}{2\omega_d}\right)^2 + i\frac{\omega\phi_0}{\omega_d}\right] \quad (6)$$

The expression (6) shows that only the group of particles with such energies that the period of transit through a disturbed region $\Delta\tau \sim \Delta\phi/\omega_d$ is less than the disturbance period T will be resonantly accelerated in the most effective way. The Pi3 disturbances just slowly propagate azimuthally, and the resonant condition denotes that after a drift around Earth an electron enters the Pi3 disturbance region with a proper phase. Particle acceleration via described mechanism is physically similar to the particle acceleration upon the transit-time heating in a synchrotron, so the discussed process may be called "geosynchrotron".

The expected effect of Pi3 impact on electron fluxes may be roughly estimated assuming that $E_\phi \sim 10$ mV/m, the azimuthal scale of Pi3 disturbance $\Delta\phi \sim 3$ h LT, for electron with energy $W \sim 1$ MeV the period of azimuthal drift at $L \sim 5$–8 according to (1) is 1–4 min. Then during the impact time electron acquire energy $W \sim eE_\phi \omega_d \Delta\phi \sim 0.2$–0.5 MeV. Typical energy spectrum at high energies may be approximated as $J \sim \exp(-W/W_0)$, where $W_0 \sim 0.3$ MeV. According to these estimates at each acceleration impact the flux increase is to be $J \sim 100$–300%. During substorm relativistic electrons can return to the acceleration region many times and subsequently increase their energy.

5. Discussion

Inference for the Electron Acceleration Mechanisms

Here we summarize arguments pro the ULF-driven acceleration:

- ULF Pc5 waves are one of the largest energy container during the storm recovery phase.
- ULF wave index was shown to be a good indicator of the relativistic electron response to magnetic storm (even better than Dst index and SW velocity) and should be taken into account by any adequate space radiation model. The acceleration of relativistic electrons is a cumulative effect of the ULF wave turbulence with a typical time scale ~ 1 day.
- Global Pc5 pulsations during the storm recovery phase can penetrate deep into the magnetosphere, in the region of relativistic electron energization;

Arguments con are as follows:

- Typical morning side Pc5 pulsations are latitudinally localized at the sub-auroral region and have a weak azimuthal electric field component in the magnetosphere;
- Directions of the electron drift and Pc5 (both toroidal and poloidal) azimuthal phase velocity are predominantly opposite.

To resolve the issues related to the ULF-driven electron energization we suggest that an increase in the power of Pi3 oscillations stimulates the acceleration and radial diffusion of seed electrons. In the process of such radial diffusion from the periphery of the magnetosphere to the internal shells additional betatron acceleration of electrons occurs. Thus, ULF Pi3 activity is a "supplier" of pre-accelerated energetic electrons to the inner regions of the magnetosphere. Here, electrons may undergo local acceleration when interacting with VLF "chorus" radiation. Statistical multifactor analysis showed that the synergistic influence of the power of ULF and VLF radiation on the fluxes of relativistic electrons is higher than the sum of the separate contributions of these factors [43]. Pi3 pulsations are closely associated with substorm, so this hypothesis highlights an additional role of substorm in the radiation belt energization.

6. Conclusions

Turbulent acceleration of magnetospheric electrons up to relativistic energies is an example of transfer of considerable energy of MHD turbulence to a small group of particles in a space plasma. There are several con factors for the electron energization mechanisms by Pc5 waves, which have not been resolved yet. We suggest that the acceleration of electrons by ULF disturbances occurs not in a regime of "geoserfotron" with Pc5 waves, but rather in regime of "geosynchrotron" with Pi3 pulsations. This fact should be taken into account by any adequate model of the electron energization. Surely, the proposed mechanism does not exclude the possibility of operation of other mechanisms, e.g., local VLF chorus-driven energization or adiabatic acceleration by recovering magnetic field.

Author Contributions

Conceptualization, V.P.; software, O.K.; data curation, V.B.; writing—review and editing, V.P. All authors have read and agreed to the published version of the manuscript.

Funding

This study of VB is supported by the grant №24-77-10012 from the Russian Science Foundation.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created in this research.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Pilipenko, V., Yagova, N., Romanova, N., et al., 2006. Statistical relationships between the satellite anomalies at geostationary orbits and high-energy particles. Advances in Space Research. 37(6), 1192–1205.

[2] Li, X., Baker, D.N., Temerin, M., et al., 1997. Are energetic electrons in the solar wind the source of the outer radiation belt? Geophysical Research Letters. 24(8), 923–926. DOI: https://doi.org/10.1029/97GL00543

[3] Kuznetsov, S.N., Yushkov, B.Y., Kudela, K., et al., 2005. Dynamics of the Earth's radiation belts during the magnetic storm of November 6th, 2001, Advances in Space Research. 36, 1997–2002.

[4] Zong, Q., Wang, Y., Yuan, C., et al., 2011. Fast acceleration of "killer" electrons and energetic ions by interplanetary shock stimulated ULF waves in the inner magnetosphere, Chinese Science Bulletin. 56(N12), 1188–1201.

[5] Reeves, G.D., Baker D.N., Belian R.D., et al., 1998. The global response of relativistic radiation belt electrons to the January 1997 magnetic cloud. Geophysical Research Letters. 17, 3265–3268.

[6] Kanekal, S.G., Baker D.N., Blake J.B., et al., 1999. Magnetospheric response to magnetic cloud (coronal mass ejection) events: Relativistic electron observations from SAMPEX and Polar, Journal of Geophysical Reserach. 104(A11), 24885–24894. DOI: https://doi.org/10.1029/1999JA900239.

[7] Vassiliadis, D., Klimas A.J., Weigel R.S., et al., 2003. Structure of Earth's outer radiation belt inferred from long-term electron flux dynamics, Geophysical Research Letters. 30(19), 2015. DOI: https://doi.org/10.1029/2003GL017328

[8] Belakhovsky, V.B., Pilipenko, V.A., Antonova, E.E., et al., 2023. Relativistic electron flux growth during storm and non-storm periods as observed by ARASE and GOES satellites. Earth Planets Space. 75(1), 189.

[9] Fok, M.H., Moore, T.E., Spjeldvik, W., 2001. Rapid enhancement of radiation belt electron fluxes due to substorm dipolarization of the geomagnetic field. Journal of Geophysical Research. 106(A3), 3873–3881.

[10] Glocer, A., Fok, M.-C., Nagai, T., et al., 2011. Rapid rebuilding of the outer radiation belt. Journal of Geophysical Research. 116(A9), A09213.

[11] Lazutin, L.L., 2013. Injection of relativistic electrons into the internal magnetosphere during magnetic storms: Connection with substorms. Geomagnetism and Aeronomy. 53(6), 716–732.

[12] Kim, H-J, Chan, A.A., Wolf, R.A., et al., 2000. Can substorms produce relativistic outer belt electrons? Journal of Geophysical Research. 105(A4), 7721–7735.

[13] Mathie, R.A., Mann, I.R., 2000. A correlation between between extended intervals of ULF wave power and storm-time geosynchronous relativistic electron flux enhancements. Geophysical Research Letters. 27(20), 3261–3264.

[14] Tan, L.C., Fung, S.F., Shao, X., 2004. Observation of magnetospheric relativistic electrons accelerated by Pc5 ULF waves. Geophysical Research Letters. 31(14), L14802.

[15] Mann, I.R., Lee, E.A., Claudepierre, S.G., et al., 2016. Discovery of the action of a geophysical synchrotron in the Earth's Van Allen radiation belts. Nature Communications. 4(1), 2795.

[16] Zhao, H., Li X., 2013. Inward shift of outer radiation belt electrons as a function of Dst index and the influence of the solar wind on electron injections into the slot region. Journal of Geophysical Research: Space Physics. 118(2), 756–764.

[17] Bakhareva, M.F., Dmitriev, A.V., 2002. Statistical Alfvenic electron acceleration in outer magnetosphere. Geomagnetism and Aeronomy. 42(1), 18–27.

[18] Shprits, Y.Y., Elkington, S.R., Meredith, N.P., et al., 2008. Review of modeling of losses and sources of relativistic electrons in the outer radiation belt I: Radial transport. Journal of Atmospheric and Solar-

Terrestrial Physics. 70(14), 1679–1693.

[19] Su, Z., Zhu, H., Xiao, F., et al., 2015. Ultra-low-frequency wave-driven diffusion of radiation belt relativistic electrons. Nature Communications. 6(1), 10096.

[20] Shprits, Y.Y., Subbotin, D.A., Meredith, N.P., et al., 2008. Review of modeling of losses and sources of relativistic electrons in the outer radiation belt II: Local acceleration and loss. Journal of Atmospheric and Solar-Terrestrial Physics. 70(14), 1694–1713.

[21] Meredith, N.P., Horne, R.B., Iles, R.H.A., et al., 2002. Outer zone relativistic electron acceleration associated with substorm-enhanced whistler mode chorus. Journal of Geophysical Research. 107(A7), SMP 29-1–SMP 29-14.

[22] Horne, R.B., Thorne R.M., Shprits, Y.Y., et al., 2005. Wave acceleration of electrons in the Van Allen radiation belts. Nature. 437(7056), 227–230.

[23] Tverskoy, B.A., 1997. Formation mechanism for the structure of the magnetic-storm ring current, Geomagn. Aeronomy, 37(N5), 555.

[24] Elkington, S.R., 2003. Resonant acceleration and diffusion of outer zone electrons in an asymmetric geomagnetic field. Journal of Geophysical Research. 108(A3), 1116.

[25] Ukhorskiy, A.Y., Sitnov, M.I., Takahashi, K., et al., 2009. Radial transport of radiation belt electrons due to stormtime Pc5 waves. Annales Geophysicae. 27, 2173–2181.

[26] Degeling, A.W., 2007. The effect of ULF compressional modes and field line resonances on relativistic electron dynamics. Planetary and Space Science. 55(6), 731–742.

[27] Sitnov, M.I., 1988. Maximum energy of particles in serfotron in the unlimited acceleration regime, Technical Physics Letters ("Pisma v Zhurnal Tekhnicheskoi Fiziki"). 14(1), 89–92.

[28] Antonova, E.E., Kirpichev, I.P., Stepanova, M.V., et al., 2009. Topology of the high latitude magnetosphere during large magnetic storms and the main mechanisms of relativistic electron acceleration. Advances in Space Research. 43(4), 628–633.

[29] Antonova, E.E., Stepanova, M.V., 2015. The problem of the acceleration of electrons of the outer radiation belt and magnetospheric substorms. Earth, Planets and Space. 67(1), 148.

[30] Tverskoy, B.A., 1968. Dynamics of the Earth radiation belts (in Russian: "Dinamika Radiatsionnykh Poyasov Zemli") Moscow. pp. 1–185.

[31] Tverskaya, L.V., Pavlov, N.N., Blake, J.B., et al., 2003. Predicting the L-position of the storm-injected relativistic electron belt. Advances in Space Research. 31(4), 1039–1044.

[32] Kleimenova, N.G., Kozyreva, O.V., 2009. Penetration of Pc5 geomagnetic pulsations to unusually low latitudes during the recovery phase of a superstrong magnetic storm of October 31, 2003, Geomagnetism and Aeronomy. 49(8), 1199–1203.

[33] Potapov, A., Guglielmi, A., Tsegmed, B., et al., 2006. Global Pc5 event during 29-31 October 2003 magnetic storm. Advances in Space Research. 38(8), 1582–1586.

[34] Marin, J., Pilipenko, V., Kozyreva, O., et al., 2014. Global Pc5 pulsations during strong magnetic storms: excitation mechanisms and equatorward expansion. Annales Geophysicae. 32(4), 319–331.

[35] Martines-Bedenko, V.A., Pilipenko, V.A., et al., 2022. Conjugate properties of Pi3/Ps6 pulsations according to Antarctica-Greenland observations. Russian Journal of Earth Sciences. 22(4), ES4006.

[36] O'Brien, T.P., McPherron, R.L., Sornette, D., et al., 2001. Which magnetic storms produce relativistic electrons at geosynchronous orbit? Journal of Geophysical Research. 106(A8), 15533–15544.

[37] Pilipenko, V.A., Kozyreva O.V., Engebretson M.J., et al., 2017. ULF wave power index for the space weather and geophysical applications: A review. Russian Journal of Earth Sciences. 17(N2), ES1004.

[38] Romanova, N., Pilipenko, V. 2008. ULF wave indices to characterize the solar wind – magnetosphere interaction and relativistic electron dynamics. Acta Geophysica. 57(1), 158–170.

[39] Antonova, E.E., Stepanova, M.V., Moya, P.S., et al., 2018. Processes in auroral oval and outer electron radiation belt. Earth Planets Space. 70(1), 127.

[40] Kozyreva, O.V., Pilipenko V.A., Engebretson M.J., et al., 2016. Correspondence between the ULF wave power distribution and auroral oval. Solar-Terrestrial Physics. 2(2), 46–65.

[41] Claudepierre, S. G., et al. (2013), Van Allen Probes observation of localized drift resonance between poloidal mode ultra-low frequency waves and 60 keV electrons, Geophysical Research Letters. 40, 4491–4497. DOI: https://doi.org/10.1002/grl.50901

[42] Tan, L.C., Shao, X, Sharma, A.S., Fung, S.F., 2011. Relativistic electron acceleration by compressional mode ULF waves: Evidence from correlated Cluster, LANL spacecraft, and ground-based magnetometer measurements. Journal of Geophysical Research. 116(A7), A07226.

[43] O'Brien, T.P., Lorentzen, K.R., Mann, I.R., et al., 2003. Energization of relativistic electrons in the presence of ULF power and MeV microbursts: Evidence for dual ULF and VLF acceleration. Journal of Geophysical Research. 108(A8), 1329.