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STOCHASTIC RESONANCE IN RUNAWAY ELECTRON KINETICS AND SOME PECULIARITIES OF HIGH ATMOSPHERIC LIGHTNING

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Recently, satellites for controlling the keeping of the nuclear test moratorium have detected some atmospheric phenomena with features similar to the nuclear explosions, i.e. high-power local energy pulse, light blast in optical and radio ranges, short impulse of γ-quanta with energy higher then 1 MeV, and so on [*Monastersky*, 1994; *Cowen*, 1994]. The later research has connected those phenomena with the high atmospheric lightnings which take place at the heights of 80-100 km. There are no clouds and thundering activities at such heights that is why it is rather difficult to understand the nature of the lightnings.

By now, the most popular model describing the mechanism of such lightnings is the one, based on the important role of so-called runaway electrons in the process of lightning discharge initiation [*Roussel-Dupre and Gurevich*, 1994]. Dreiser was the first, who investigated the nature and reasons of runaway electrons appearance in the 50-th [*Dreiser*, 1958]. He suggested, that because of non-monotonic dependence of the electron cross-section on its energy, the dynamic friction force (which depends on electron collisions with gas atoms and radiative losses) also has non-monotonic behaviour. Thus, the energy losses of the electron drifting with the velocity higher than some critical value are much less than those for electron drifting with smaller velocity. That lead to appearance of the distribution with two stable energy states (low energetic state, i.e. considerably slow non-relativistic electrons and high energetic state, i.e. runaway relativistic electrons). So, as it was shown in [*Babich*, 1995], the distribution with two groups of electrons of different energies would appear.

Stochastic self-excitation is a form of such a well-known phenomenon as a stochastic resonance. For the first time, stochastic resonance was predicted in [*Benzi et al.*, 1981] for describing long term climate oscillations. Since that time the stochastic resonance has been found in various potential systems with double minimum potential, but there are examples of successful application of the stochastic resonance theory for description of non-potential systems [*Crisanti and Vulpiani*, 1993].

At present, the best studied type of the stochastic resonance is the amplifying one, i.e. if a double state system is subjected to the simultaneous action of noise and a periodic signal, then under some conditions the phenomenon of signal to noise ratio increase can take place [*McNamara and Wiesenfeld*, 1989]. Unlike the ordinary resonance, where the effect of signal amplitude amplification appears at the matching of the eigenfrequencies of the system and frequencies of the external signal, the stochastic resonance appears when the frequency of the external signal matches the average frequency of the system jumps from one stable state to another under the action of noise. That means that during stochastic resonance, the noise energy is partly transferred into the energy of regular oscillations.

In our case there is no external signal, but, however, white noise contains oscillations of all frequencies, which means that in the noise spectrum one can find periodic oscillations of any necessary frequency. That is why, instead of amplifying the external periodic signal, as in the case of ordinary stochastic resonance, under stochastic self-excitation amplification of one of the eigenfrequencies of the white noise which matches the average frequency of the spontaneous jumps of the system from one state to another under the action of noise will take place because of noise oscillations with other, non-resonant, frequencies. That will lead to generation of almost periodic oscillations.

For description of particle motion in the field of some stochastic force one should solve the Fokker-Plank equation. In our case this equation can be written in the following form:

$$\frac{\partial W(p,t)}{\partial t} = \frac{\partial}{\partial p}\left(F(p) - eE + D\frac{\partial}{\partial p}W(p,t) \right), \qquad (1)$$

here $F(p)$ is the dynamic friction force of the electron, eE is the electric force, D is the noise amplitude, p is the electron impulse. $W(p,t)$ is the probability of particle having impulse p at the moment t.

In [*McNamara and Wiesenfeld*, 1989] the exact analytical solution for particle motion in the system with two stable states and the external periodic force was obtained. According to that paper, a peak at the frequency of spontaneous particle jumps from one stable state to another was observed in particle spatial spectrum.

To verify existence of the stochastic self-excitation phenomenon in runaway electron kinetics, the authors have performed numerical simulation of electron motion in the external electric field under the action of non-linear dynamic friction force. This problem is commonly solved under the suggestion that electron is subjected to the action of the external electric field and randomising dynamic friction force [*Babich*, 1995]. However, since the electron drift in the dense gases is essentially stochastic, electron in the course of its motion through gas permanently experiences occasional interactions with gas atoms as well as with fine-scale fluctuations of the electric field in plasma. That is why it seems more plausible to solve the Langevin equation for simulating electron motion in gas. This equation, in the contrary to [*Babich*, 1995], contains a term describing separate occasional interacting acts. So we have solved the following equation:

$$\dot{\vec{p}} = e\vec{E} + \vec{F} + \sqrt{D}\vec{\xi}(t), \tag{2}$$

here $\vec{p}$ is the electron momentum, $\vec{F}$ is the dynamic friction force, $\sqrt{D}\vec{\xi}(t)$ is the term describing the stochastic force.

According to [*Babich*, 1995], the dynamic friction force can be written as follows:

$$\vec{F}(\varepsilon) = -\left(\frac{\vec{p}}{p}\right)F(\varepsilon) = -\left(\frac{\vec{p}}{p}\right)\left(\frac{N}{N_1}\right)L(\varepsilon), \tag{3}$$

here N is the concentration of gas particles, N_1=3.54×10^{16} cm^{-3} is the concentration of gas particles under gas pressure P=1 Tor and temperature T=300 K, $L(\varepsilon)$ is the electron energy losses at a unit distance, ε is the electron energy; sign «–» in (3) refers to the opposite directions of the vectors $\vec{p}$ and $\vec{F}$.

For numerical solution of this equation we have supposed E=10 kV/cm, according to [*Imianitov*, 1988] such fields can be observed in the atmosphere during lightning activity, $L(\varepsilon)$ has been presented as a Lagrange polynom of the seventh order. The most important points for this polynom have been taken from [*Babich*, 1995]. The result of the interpolation is presented in Figure 1.

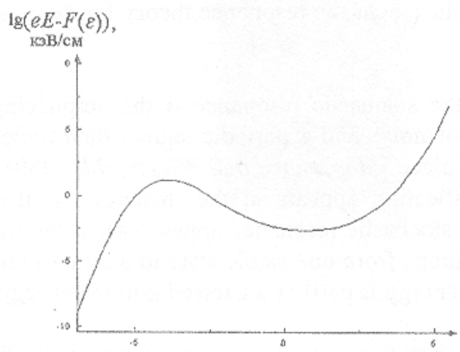

Fig.1 The dependence of the electron energy loss function on its energy (logarithm scale).

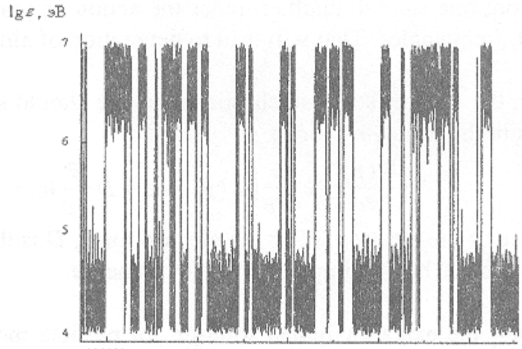

Fig.2. Time dependence of the electron energy.

The noise amplitude has been supposed to be equal to $D = 10^3$ eV/cm, which is comparable with the force necessary for transferring from one stable state to another.

The time dependence of the electron kinetic energy is shown in Fig.2. It is easy to see that owing to occasional collisions with gas particles, electron suffers jumping from the non-relativistic state to runaway one and *vise-versa*. Certainly, the computation of equation (2) can't lead to such results without including the stochastic part of dynamic friction force.

The dependence $\varepsilon(t)$ was numerically expanded into the Fourier series by means of fast Fourier transformation algorithms. The results of that expansion are presented in Fig.3.

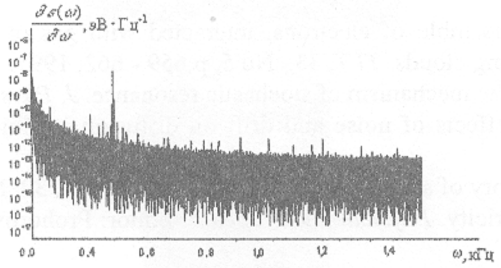

Fig.3. Spectrum of electron energy oscillations in the air at the height of 40 km.

In Fig.3 one can see a peak at the frequency of 0,5 kHz. That proves the existence of the stochastic self-excitation for the electron impulse oscillations.

Let's suppose that after a collision of a runaway electron with a gas atom its energy drops down to several keV. This process goes with emission of bremsstrahlung radiation. If electrons in their motion don't collide with each other, then the numbers of electrons transferred from the runaway state to non-relativistic one and back are the same, that means that electrons are uniformly distributed over the energy oscillation phases. However, if due to some collective process, electron phasing occurs, it will lead to bremsstrahlung radiation modulation with the frequency of stochastic self-excitation. The possibility of occurrence of bremsstrahlung radiation modulation was noted in [*McCarthy and Parks,* 1992]. The experimental observation of such modulation could prove the important role of runaway electrons in initiation of the high atmospheric lightning.

According to (3), the function of the electron energy losses (the dynamic friction force) depends on gas particle concentration, which, in its turn, varies with height. We have calculated the frequency of stochastic self-excitation for a lightning discharge in runaway electron kinetics for different heights. The curve of the self-excitation frequency versus height of the lightning is presented in Fig.4.

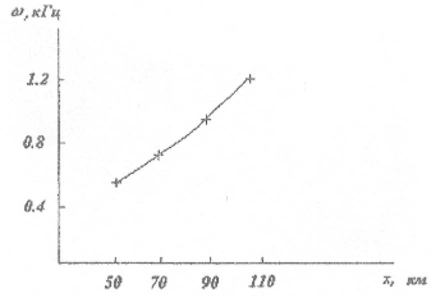

Fig. 4. Self-excitation frequency versus the height of the lightning.

So, in this paper we have demonstrated the possibility of stochastic self-excitation of the electron energy or impulse oscillations between two stable states in plasma systems with runaway electrons. This phenomenon is a kind of such well-known phenomenon as a stochastic resonance.

This self-excitation in combination with some collective processes can lead to modulation of bremsstrahlung radiation with the frequency of self-excitation. Observation of such modulation with necessary frequency could prove the responsibility of runaway electrons for high-atmosphere lightning initiation.

References

Monastersky R. Puzzling atmospheric bursts spark interest. *Science News*, 145, No.7, p.100-101, 1994

Cowen R. Enigmatic bursts show their true colors. Science News, 146, No.6, p.87, 1994.

Roussel-Dupre R, Gurevich A.V. On runaway breakdown and upward propagating lightning. *Phys. Rew.* E, 49, No.3, p.2257 - 2261, 1994.

Dreiser H. To the theory of "runaway" electrons. *Second international conference for peaceful usage of nuclear energy,* Geneva 1958, p.170-180

Babich L.P. Bi-stability of the ensemble of electrons, interacted with gas of neutral particles in the electric field. Application to the field of lightning clouds. *TVT*, 33, No 5, p.659 - 662, 1995.

Benzi R., Sutera A., Vulpiani A. The mechanism of stochastic resonance. *J. Phys*. A, 14, p.L453 - L457, 1981.

Crisanti A., Vulpiani A. On the effects of noise and drift on diffusion in fluids. *Journal of Statistical Physics*, 70, No.1/2, p.197-212, 1993.

McNamara B., Wiesenfeld K. Theory of stochastic resonance, *Phys. Rev.* A, 39, No 9, p.4854 - 4869, 1989.

Imianitov I.M., Atmospheric electricity. *Physical encyclopedia*. Editor: Prohorov, M.: Sovetskaya encyclopedia, 1988, p. 653.

McCarthy M.P., Parks G.K. On Modulation of X-Ray Fluxes in Thunderstorms. *Geophys. Res. Lett.* 97, No D5, p.5857 - 5864, 1992.