INFLUENCE OF ACTIVE COSMIC FACTORS ON THE DYNAMICS OF NATURAL INFRASOUND IN THE EARTH'S ATMOSPHERE

V. KOSHOVYY[1], O. IVANTYSHYN[1], V. MEZENTSEV[2], B. RUSYN[1], M. KALINICHENKO[3]

[1] Karpenko Physico-Mechanical Institute, National Academy of Sciences of Ukraine,
5, Naukova Str., 79060, L'viv, Ukraine
E-mail: volodymyrkoshovyy@gmail.com; o.ivantyshyn@gmail.com; b.rusyn.prof@gmail.com
[2] Lviv Centre of the Institute of Space Research, 5a, Naukova Str., 79060, L'viv, Ukraine
E-mail: m5z5ncev@gmail.com
[3] Radio Astronomical Institute of the National Academy of Sciences of Ukraine, 4, Str. of Arts,
61002, Kharkiv
E-mail: kalinich@ri.kharkov.ua

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Abstract. Hypothesis about the extended interpretation of the term "geoefficiency" of active space factors is considered. A stable correlation between the dynamics of the average monthly values of atmospheric infrasound, the entry of galactic cosmic rays into the Earth's atmosphere and International sunspot number has been experimentally confirmed and quantified.

Key words: galactic cosmic rays, atmospheric natural infrasound, correlations.

1. INTRODUCTION

The problem of space weather is an important area of the solar-terrestrial physics. It also includes investigation of the effect of *active cosmic factors* (ACFs) on the state and physical processes in the *near-Earth space* (NES) environment. This effect is often defined as a "geoefficiency" of ACFs. Geoefficient manifestations of *solar activity* (SA) and the study of the relationship between events on the Sun and the corresponding changes in a state of solar wind, magnetosphere, ionosphere, and in surface layers of the NES are the key issues in this problem [1–3]. Most commonly consider three spontaneously powerful SA-related events that affect NES components are, in particular: solar wind (takes out interplanetary magnetic field into the interplanetary space), solar flares (accompanied by powerful emissions of large streams of the *solar energetic particles* (SEPs)), *coronal mass emissions* (CMEs) (after a few hours or days can reach the Earth, cause perturbations of the *geomagnetic field* (GMF), ionosphere disturbances, decrease in the intensity of *galactic cosmic rays* (GCR)).

At present, the existence of statistically stable relationships between the parameters of SA dynamics (the *International sunspot number* (ISN) (also known as the Wolf's number) is defining total sunspots number) and the NES components environment state and processes in them (meteoparameters, changes of GMF level and surface pressure, processes in the Earth's biosphere, etc.) has been reliably established. However, not all parts of the solar-terrestrial relationships have been equally studied, in particular the specific physical mechanisms of generating the processes that accompany the action of ACFs on the NES environment. Currently, it is mainly considering the hypothesis that the probable cause of the NES components reactions to such action is the GMF fluctuations. Much less attention is paid to the studying of possible other consequences of this influence, in particular the stimulation by it the generating the atmospheric natural infrasonic field of cosmic origin (further in the text – natural infrasound).

Article aims to clarify some quantitative estimates of solar-terrestrial connections in the above sense and considers the term "geoefficiency" of ACFs (SEPs, GCR, etc.) in a broader interpretation. This means that in the process of interaction of ACFs with environment of the NES components, disturbances of other geophysical fields (not only GMF), in particular natural infrasound, can occur. On the basis of long-term experiments authors investigate the specific correlations between dynamics of some ACFs and the natural infrasound.

2. NATURAL INFRASOUND OF COSMIC ORIGIN

The ACFs geoefficiency is determined by the situation on the Sun, solar cycle phase, orientation of the Earth's magnetic dipole etc. [1–3]. Among them the most geoeffective are: 1) solar wind – geoefficiency is determined by its speed, density and direction of the magnetic field (the greater the speed, the stronger the frozen electric field, which affects the nature of the interaction of the solar wind with the Earth's magnetosphere); 2) CME – the most geoefficient phenomenon in the Sun – Earth system (at propagating from the Sun they pass into Interplanetary CME (ICME) and a shock wave (its velocity > 2000 km / s) is formed in front of them, the collision of which with the Earth's magnetosphere leads to GMF perturbations, release of energetic particles from the Earth's radiation belts, perturbations ionosphere, etc.); 3) solar flares and shock waves generate in the corona the high-energy SEPs, which enter the Earth's magnetosphere, modificate a radiation situation in the NES, additionally ionize the ionosphere, causing the GMF perturbations, and reach the Earth's surface in about an hour or more.

The average annual fluxes of electrons in the outer radiation belt change with the phase of the solar cycle. The inner radiation belt, formed by the action of GCR due to neutron decay, is a source of erupting energetic protons during GMF perturbations. Its state also depends on the SA phase, because the fluxes of GCR decrease at the maximum of the solar cycle and increase at its minimum. Getting into the Earth's atmosphere through the formation of secondary particles, GCR affect the formation of the Earth's climate. The GCR and SA flows anticorrelate with each other (the higher SA level, the smaller the flow of GCR, and *vice versa*).

Natural infrasound. Many high-energy natural and man-made dynamic processes (storms, tsunamis, earthquakes, volcanic eruptions, rocket launches, explosions, etc.) generate acoustic waves of the infrasonic range in the Earth's atmosphere [4]. In addition, in the Earth's atmosphere is constantly present a natural infrasound of cosmic origin caused by the energy impact of ACFs. Possible mechanisms for the conversion of energy of cosmic origin into acoustic oscillations in the Earth's atmosphere are presented in Figure 1 [4]. Periodic perturbations of the natural ISF are being caused by: morning and evening terminator (mostly the high frequencies), solar-lunar tidal forces (create oscillations of the atmosphere and deformations of the Earth's crust). Sporadic disturbances of the natural infrasound are stimulated by: solar eclipses, local shading, movement of clouds (due to the formation of instabilities during the movement of light and shadow boundaries and atmospheric zones with different coefficients of absorption of solar radiation, or in the process of optical-acoustic transformations), by movement in the atmosphere of meteoroids (due to the intensive release of energy during the entry in the atmosphere and combustion of these objects), etc.

It is currently believed the most effective sources of disturbances of the natural ISF of cosmic origin are the solar terminator, solar eclipses, SEPs and GCR. The following scheme of this influence has been considered in the publication [4]: cosmic factors (electromagnetic waves, particle fluxes) → transformation into the natural atmospheric infrasound → influence of infrasound on terrestrial processes. Its authors did the following: 1) identified the main ACFs (SA, SEPs, GCR and meteor showers) that influence on formation of the natural atmospheric infrasound; 2) took into account the fact that natural atmospheric infrasound can be also generated by the action from "below" a number of high-energy terrestrial phenomena (earthquakes, etc.); 3) formulated the problem of selecting of signals of cosmic origin infrasound from total infrasonic noise in the near-surface layer of the atmosphere.

In the same work, authors proposed model of formation of helio-induced perturbations of the natural ISF in the Earth's atmosphere (Figure 1). The proposed model takes into account both the consistent impact on the environment (by different physical mechanisms) of the enhanced solar wind (including SEPs, their magnetic fields etc.), and the overall impact of these factors. The model also presents the scheme of origin the natural infrasound by the influence of stimulation the NES environment by the SA processes: formation in the atmosphere the spatio-temporal distribution of ions and aerosols by the ACFs action → formation of significant spatially inhomogeneous changes atmosphere transparency → formation thermal inhomogeneities in the atmosphere due to its modulation → generation the natural atmospheric infrasound at interaction of solar radiation with thermal inhomogeneities of the atmosphere.

Analyzing the transformations on this scheme must be borne in mind: 1) at low SA level, the ionization process in the atmosphere is determined by the GCR influence; 2) with increasing SA level, the intensity of GCR and, accordingly, the intensity of ionization processes decrease, and already SEPs determine these processes, and ions become centers of cluster formation and water condensation; 3) SEPs form aerosols only in the upper atmosphere due to low their permeability, while GCR – throughout the atmosphere; 4) the presence of aerosol particles leads to spatially heterogeneous heating of the atmosphere due to absorption of solar energy by it, shading, condensation of water vapor on aerosols and ions, clustering of water molecules, changes in the rates of chemical reactions in the atmosphere; 5) the energy of these processes leads to the fact that even a small amount of energy transferred by SEPs and GCR stimulate a significant release of latent energy into the atmosphere and also corresponding forming of the bulk forces, which generate infrasonic waves in the atmosphere.

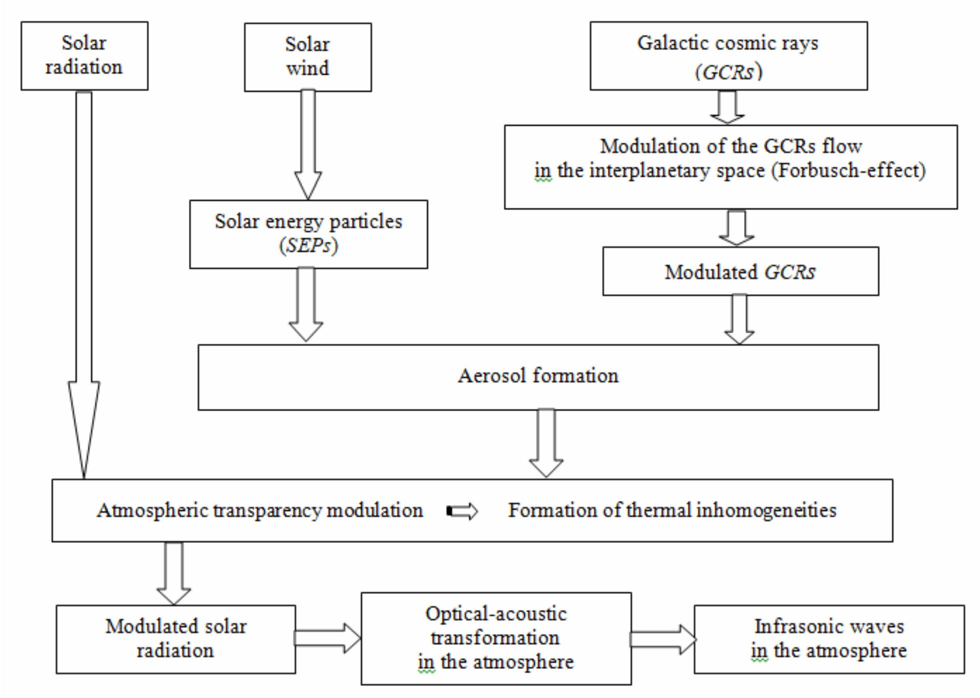


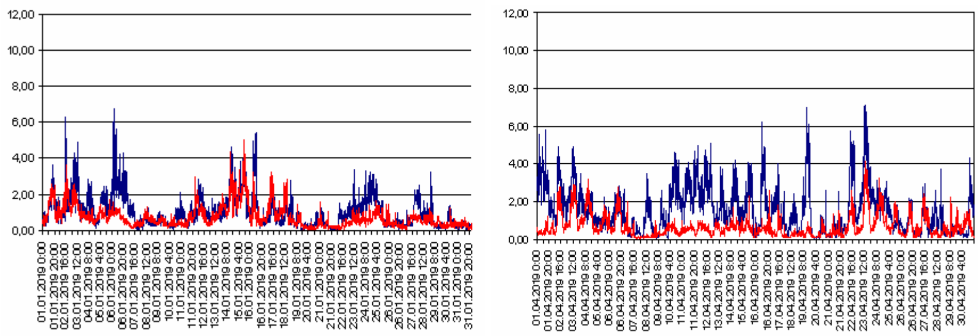
Fig. 1 – Schematic model of the mechanism of formation of natural atmospheric infrasound under the action of cosmic factors.

Thus, the model reflects possible the GCR and SA effect on the atmosphere and generation of natural atmospheric infrasound. But it requires the experimental confirmation, results of which are presented below.

Polygons for natural infrasound measuring and the used data. The authors conducted long-term experimental studies of the natural infrasound during the 23^{rd}–24^{th} solar cycles simultaneously on the protected areas of the transboundary (Polish-Belarusian-Ukrainian) UNESCO biosphere reserve (Shatsk, Volyn' region) and on the urban areas (West Ukraine: L'viv (L'viv oblast') and Kamianets-Podilskyi (Khmelnytskyi oblast')). The distances between these observational test polygons are ~ 200–300 km. The use of nature reserves as experimental polygons for measuring natural infrasound of cosmic origin has minimized the impact of industrial noise and anthropogenic interference on the results of observations of the natural infrasound.

It has been investigated: the specific dependences SF (at medium latitudes in the ranges 0.01–1.0 Hz and 1.0–10.0 Hz) on the GCR intensity and ISN value. Data used: 1) measurement data of atmospheric infrasound by own technical means based on infrasound sensors; 2) data of the Moscow neutron monitor on the GCR intensity; 3) Internet data on dynamics of SA processes, in particular on changes of ISN values during the 23^{rd} – 24^{th} solar cycles period.

Detecting perturbations of the natural infrasound. In the paper have been investigated the properties of experimental random time realizations of the natural infrasound (typical ones are presented in Figure 2) and the criterions of detection in them the helio-induced perturbations.



a) b)

Fig. 2 – (Color online). 10-minute experimental samples of envelopes of perturbations of the atmospheric natural infrasound registered in the range (0.01–1.0) Hz on the test polygons: L'viv (blue line), Shatsk (red line); a) – January 2019; b) – April 2019.

In this aim, on the basis the model of modulated random process, it was analyzed the signals registered on long and short time intervals on such parameter as an envelope of the signal A(t) that allowed to demonstrate the influence of solar processes on formation of perturbations of natural infrasound. And on the basis of qualitative analyzing the signals registered within 4–6 hours, have been showed the next: a) the average systematic trend is absented; b) amplitude of fluctuations does not noticeably increase and does not decrease; c) typical periods of fluctuations do not noticeably change. With that in mind, such fluctuations (for several hours) of the natural infrasound one can consider as realizations of a stationary random process [5], the main non-random characteristic of which is the correlation function $R(\tau)$. That allows estimating the degree of correlation between parameters of SA and the natural infrasound.

For random signals, the shape of $R(\tau)$ does not change until the properties of the signals themselves aren't changing. At our situation, its declining with increasing τ indicates the absence of regular oscillations in the received signal and decrease in the statistical relationship between the signal samples. This confirmed the correct choice of the process model and allowed to estimate the average spectra of undisturbed and helio-disturbed infrasound. As an average spectrum of a signal presents a spectral density of a stationary random process, an envelope of oscillations of the natural infrasound (in the sense of the Hilbert transformation) was chosen to find the moment of onset and duration of perturbations.

The analysis of the registered signals showed that the daily changes A(t) are cyclic, *i.e.* contain approximate repeatability of values and random deviations from it. This allowed to consider them as time realizations of the *periodically correlated random process* (PCRP), for which mathematical expectation and standard deviation are non-random periodic functions of time (in our case, this is a day [5]). At the same time, for physical reasons and results of comparison of experimental records of the processes of SA and natural infrasound (Figure 3) follows: 1) the envelope values of undisturbed natural infrasound do not exceed the threshold determined by a mathematical expectation and standard deviation of these PCRPs for each moment of time; 2) the moment of exceeding and the time of being of the envelope above it determine the time of the excited state, one of the reasons of which are solar flares. The analysis allowed studying statistics of moments of onset and duration of the excited state after the onset of the solar flare and assessing the degree of correlation between solar flares and helio-induced disturbances of the natural infrasound.

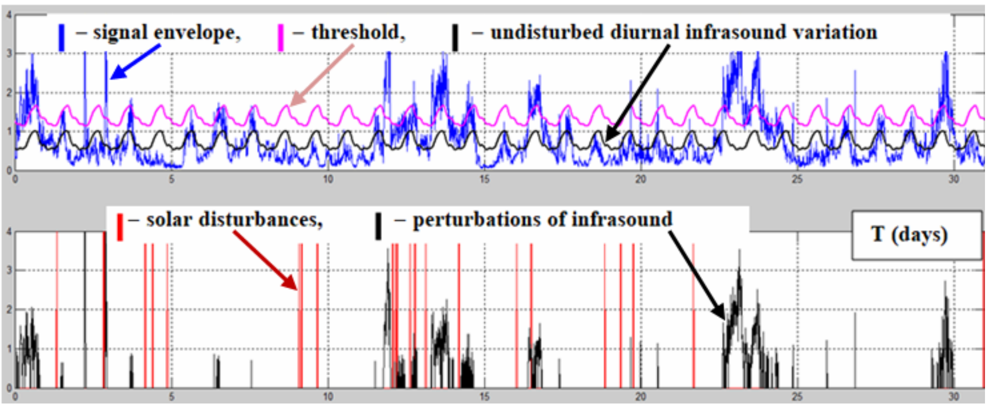
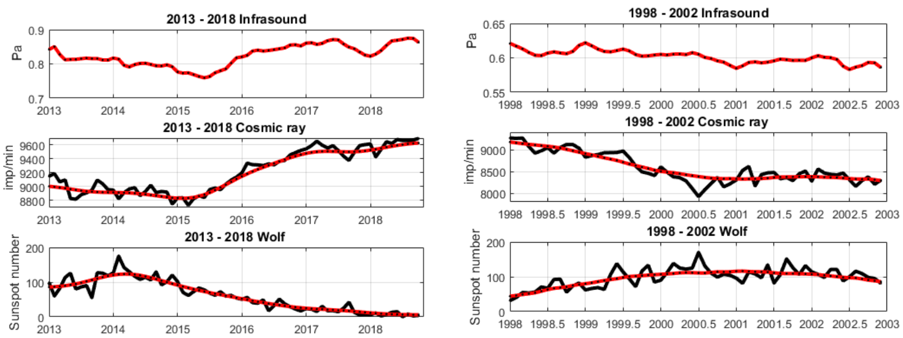


Fig. 3 – (Color online). Comparison of the processes of solar activity and natural infrasound. Above: a daily course of undisturbed natural infrasound (black); envelope of change of natural infrasound disturbed by the solar flares (blue); the threshold (sum of a mathematical expectation and standard deviation of the PCRP) (red). Below: solar disturbances (red); infrasound perturbations (black).

3. BASIC RESEARCH

At present, the influence of SA on the Earth's processes is studying in detail [1–3]. However, its effect on the lower atmosphere in a part of stimulation of perturbations of natural infrasound still insufficiently studied ([5]).

Dynamics of natural infrasound on long time scales is determined by multifactorial external influence. Figure 4 presents the results of studies the low frequency trends of changes (in the 24th and 23rd solar cycles) the perturbations of the natural atmospheric infrasound caused by the SA influence, average monthly GCR values and ISN. The graphs show a negative correlation between the change dynamics of the average monthly values of the GCR and ISN, and demonstrate the similar dependence and stable relations between GCR inflows and the occurrence of disturbances of the natural infrasound in the atmosphere.



a) b)

Fig. 4 – (Color online). Results of simultaneous long-term observations of the dynamics of changes during the 24th (a) and 23rd (b) cycles of solar activity of the parameters of the next processes: upper panels – envelope of disturbances of the natural infrasound; middle panels – monthly mean values of GCR intensity (black line) and their trend (red line); bottom panels – monthly mean the ISN values (black line) and their trend (red line).

Figure 5 demonstrates the dependences of the envelope values of disturbances of the natural atmospheric infrasound on the intensity of GCR arrival. As can be seen, the relationship between these parameters is close to linear one, and the correlation coefficients are equal 0.87 and 0.70 for the 24th and 23rd cycles, respectively. This difference has a physical meaning as during the 23rd cycle the monthly values of GCR were significantly lower than during the 24th one. At the same time, these results simultaneously show a noticeable scatter in the values of disturbances envelope of the natural infrasound relative in relation to a line of linear regression constructed by the least squares method. Such line characterizes the linearity of this relationship. The scatter one may explain by the influence of other factors (SCRs, meteorological phenomena, etc.) on the disturbances of the natural infrasound, and that other factors may have a nonlinear influence.

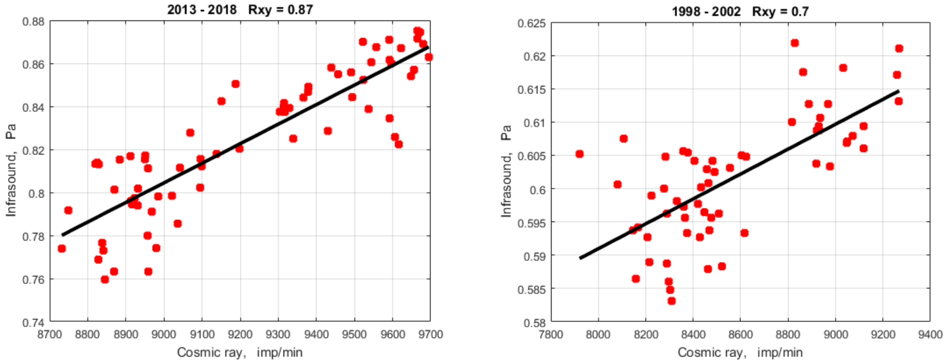


Fig. 5 – (Color online). Relationship between dynamics of disturbances of the natural atmospheric infrasound and dynamics of the GCR intensity for the 24th (at left) and 23rd (at right) solar cycles (red dots – experimental measurements, black line – linear approximation).

Dynamics of the natural infrasound disturbances on short time scales. For analysis, it have been jointly considered the characteristic features of these processes that occurred in September 2017, and of simultaneous events in the Sun (coronal mass emission, X-ray radiation) and in the NES (the perturbed geomagnetic field) (Figure 6). Active area of 2673 located in the south-western part of the solar disk with heliographic coordinates (S10 W30) (Figure 6a), became the source of six solar flares on September 6, 2017. Among them: two flashes of the X class – X2.2 solar flash that started at 08:57:00 UT and lasted 20 minutes, and X9.3 solar flash that started at 11:53:00 UT and lasted 17 minutes (data TESIS, NOAA GOES). The maximum of flares was occurred at 09:10:00 UT and at 12:02:00 UT respectively. On September 7, 2017, the same active area became the source of eleven solar flares.

According to SOHO LASCO, active processes (solar flares) on the Sun surface have been took place on 09/06/2017 at 12:06:05 UT (Figure 6a), and CME with an angle of 145° have been recorded at 12:06:05 UT (Figure 6b). After ~ 37 h from the beginning of the X2.2 solar flare, the start of the magnetic storm was also recorded (top panels in Figures 6c, 6d, 6e). According to WDC for Geomagnetism, Kyoto, the magnetic storm began on 07/06/2017 at 10:00 PM UT. The decrease in the Dst index reached –142 nT, and the duration of the main phase of the magnetic storm was 5 hours. At 13:00 UT 09/09/2017, the beginning of the second magnetic storm, corresponding to a delay of ~ 49 h from the start of the X9.3 solar flare, which was followed by the CME, was recorded. The decrease in the Dst index reached –124 nT, and the duration of the main phase of the magnetic storm was 6 hours. In Figure 6 (6c, 6d, and 6e, bottom panels) it is presented the dynamics of the power spectrum change of the natural infrasound before and after the solar flare, corresponding that is a result of the author’s researches. The presented records demonstrate the strong correlation between the active processes in the Sun and caused by them processes in the NES, in particular by such geophysical fields as geomagnetic one and natural atmospheric infrasonic one.

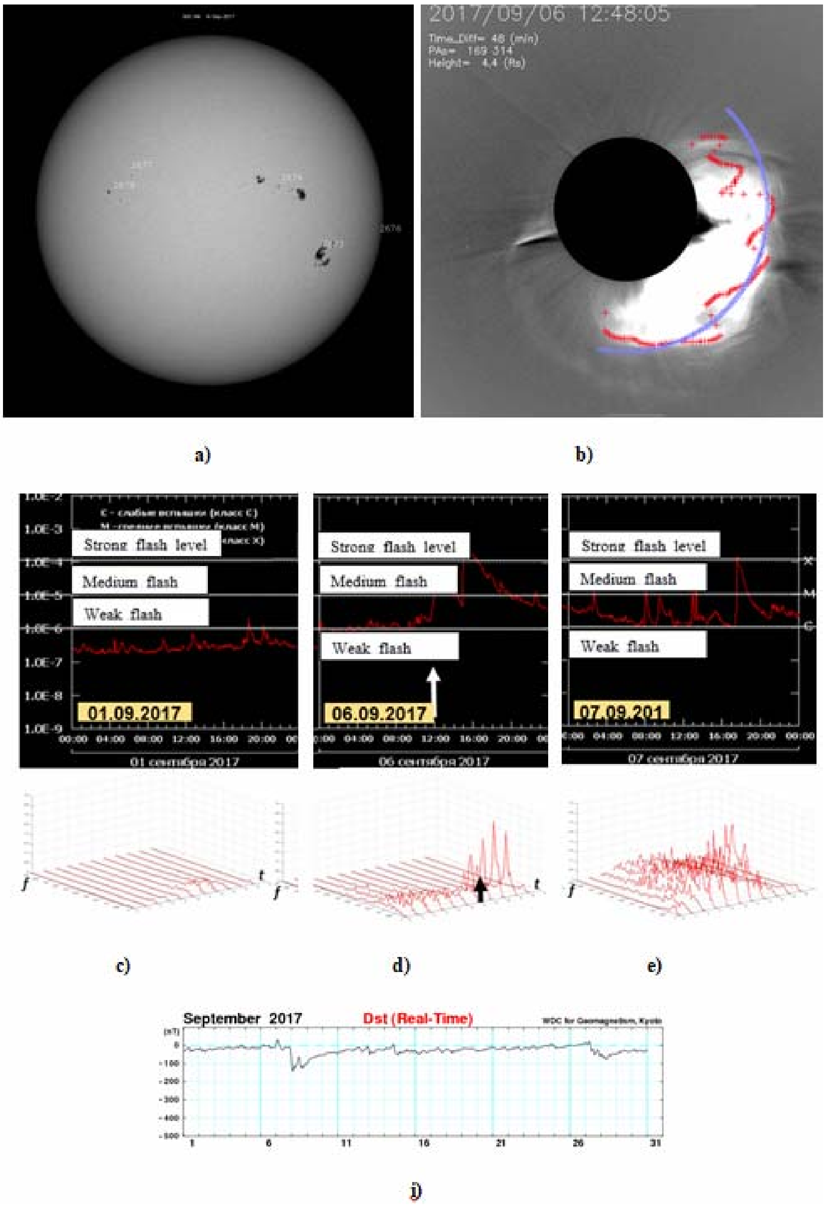


Fig. 6 – (Color online). The events registered simultaneously on the Sun and in the near-Earth space: active areas on the Sun surface that took place on 09/061/2017 (a); coronal mass ejection that took place on 09/061/2017 at 12:06:05 UT (b); X-ray radiation intensity of the Sun registered (according to TECIS) on 09/01/2017 (c, top panel), 09/06/2017 (d, top panel) and 09/07/2017 (e, top panel); the time dependence of the geomagnetic activity index Dst registered (according to WDC for Geomagnetism, Kyoto) during a period of 09/01/2017 – 09/31/2017 (i); dynamics of the power spectrum change of the natural infrasound registered before and after the solar flare on 09/01/2017 (c, bottom panel), 09/06/2017 (d, bottom panel), and 09/07/2017 (e, bottom panel).

4. CONCLUSIONS

An extended interpretation of the term “geoefficiency” of active space factors is proposed, which, in contrast to the traditional one, suggests the possibility of origin of disturbances not only of the geomagnetic field but also of other geophysical fields, including natural atmospheric infrasound.

For the first time, it have been experimentally established: a) availability a stable correlative connection and similarity of the dynamics of changes in the average monthly values of natural atmospheric infrasound and the inflow of galactic cosmic rays into the Earth’s atmosphere during long time intervals (during the 24^{th} and 23^{rd} solar cycles correlation coefficients between them were equaled 0.87 and 0.70, respectively); b) linearity of the relationship between the low-frequency trend of an envelope of the disturbances of the natural atmospheric infrasound and GCR inflow intensity; c) scatter of values relative to direct of linear regression conditioned by influence of other factors; d) a short-term increase in the intensity of the natural atmospheric infrasound on the short time intervals (up to several days) caused by the growth of energy of solar wind and solar cosmic rays (such effects has been demonstrated on the example the dynamics of Sun’s activity, geomagnetic field, and natural infrasound in the period 01.09.2017 – 07.09.2017; e) that in the absence of active solar events, the intensity of natural infrasound is low; i) the appearance of sufficiently intense perturbations of the natural infrasound field by 4 hours after active solar event that corresponds to a period during which high-energy particles of the solar wind reach the Earth’s atmosphere.

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