Space Weather Influence on Technological, Biological and Ecological Systems: Some Major Results of Complex Investigations Conducted in Azerbaijan

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Some major results of studies carried out in Azerbaijan on the possible influence of space weather, namely, periodical changes of solar and geomagnetic activities as well as non-periodic large solar energetic events on certain technological, ecological and biological systems are described in this review paper. Special attention is paid to the results of investigations on influence of violent solar events and severe geomagnetic storms on the above-mentioned systems.

Introduction

"Space Weather" phenomenon, which is one of the important components of the Solar-Terrestrial Physics (STP), is determined by the most varied interactions between the Sun and interplanetary space, and the Earth. Space weather's changes can negatively affect not only technological [1], but also ecological and biological systems, including human life/health and all-kind of human activities [2, 3].

Our changing and increasingly technology-dependent world is getting more sensitive to solar and geomagnetic activity, to changes in these activities and their manifestations on the Earth [4]. For getting more and better knowledge about solar and geomagnetic activities' potential effects on the above-mentioned systems, particularly in middle geographic latitudes, we have initiated investigations on these problems conducted by the "*Group on study of solar-terrestrial relations and space weather effects*" in the Azerbaijan National Academy of Sciences (ANAS) (see: [5-7]). These investigations cover monitoring, analysis, and theoretical and experimental studies of space weather effects as well as application of obtained results. Joining efforts of highly skilled scientists and specialists from different fields of science and technology allows studying the space weather and its impacts as an integrated system. We are studying the possible influence of space weather factors in the following research areas: a) *space weather influence on technical and engineering systems* (scintillation of communication and navigation microwave radio signals, electric power grids, oil production activity, functioning of oil-gas transportation pipelines, etc.); b) *space weather effects on human life and health* (virus-epidemic diseases, influenza, human brain functional state, cardiovascular diseases, sudden cardiac death mortality, biologically active points of human body, ophthalmologic diseases, thalassemia, traffic accidents, etc.) and *ecological systems* (climate changes, beekeeping, plants, etc).

Part of major results of these complex investigations on possible influence of periodical changes in solar and geomagnetic activities, as well as non-periodic large solar energetic events and major geomagnetic storms on certain technological (power supply systems), biological (human brain) and ecological (beekeeping) systems, without a detailed description of used methods, mathematics and/or physics, and big amount of figures, is provided in this review paper which is based on the original research works. These studies include an influence of violent solar events (such as in October-November 2003) and severe geomagnetic storms on the considered systems as well.

Impact of major and severe geomagnetic storms on the electric power transmission and supply systems in Azerbaijan

The effects of space weather on ground-based technology are mostly due to the varying geomagnetic field. The rapidly varying geomagnetic field may induce geo-electric fields across the Earth's surface. The *geomagnetically induced currents* (GICs) in electric power transmission systems during a geomagnetic storm are produced by the geo-electric field, which is determined by the large electric currents continuously flowing in the magnetosphere and ionosphere and by the structure of the Earth's conductivity.

Today's electrical grids are more susceptible to solar-storm disruption than their more localized predecessors because of the large geographical areas they cover and their interconnected and electronically-equipped nature.

Space weather effects on electric power transmission grids and transformers are widely investigated, mainly, for high geographical latitudes (see, for example [1, 8]), but there are signs that GIC can have significant risks to ground-based systems at low-latitude and mid-latitude locations, which were reported, side by side with our investigations [9, 10], recently in [11].

We have investigated an impact of geomagnetic storms of various strengths on developing electric power industry of Azerbaijan (mid-latitude location), its operational reliability, on the base of detailed (on daily base, with time span of 1994-2005) and accurate technical-engineering data (power system behavior from almost all of power controlling points: failures, breakdowns, voltage oscillations, etc.) and relevant controlling measurements made by the Dispatcher Office of the Joint Stock Company "AzerEnerji" (Azerbaijan State Energy Company) and "Barmek-Azerbaijan" EN Ltd on our request. An attention was concentrated on effects of so-called solar extreme events which had a place in July 2000, October-November 2003 (the largest in the Solar Cycle 23) as well as in September-October 2001, April 2002, November 2004, January 2005, etc. Daily monitoring and analysis of space weather conditions allowed coordinating joint activities of astrophysicists and power engineers/dispatchers/scientists and creating a digital database for the considered period.

Taking into account the complexity of considered problem we have introduced, on the scientific-technical basis and after

consultations with specialists, an "index" style of breakdown severity classification, extracting non-significant and pure technical-type events. Spectral analysis was applied.

Our studies have revealed that the number of serious breakdowns (which can not be explained only with the reason of technical character), power cuts and power line disturbances are significantly increased only during severe stormy days, when the geomagnetic field displayed sharp changes. There were registered the increased (comparative to relative quiet days with "usual" technical problems) system failures such as differential phase protection, earth protection failure, sudden relay operations (trippings), voltage drops, saturation of power transformers, reactive power consumption, harmonics, stray flux, overheating, black-out.

For each interruption case relevant oscillograms were registered which show clearly number of harmonic oscillations in the current and voltage, disrupting the signal waveforms that were registered in saturated transformers. Probably, the comparatively extra voltage fluctuations produced in the transformer, caused false relay operations (trippings) of the protective devices that suddenly prevented power lines from functioning and lead to some additional non-significant losses in various equipments.

Daily data on failures and power distribution system behavior in years 2002-2005 created by "Barmek-Azerbaijan" EN Ltd in grand Baku area (Absheron Peninsula) was subjected to spectral/Fourier analysis (Fig.1). After "cleaning" the data from such subjective factors as seasonal influence, pure technical kind of effects, etc., the remained data revealed quasi-year (annual), quasi-two-year, 60-days, 3-months and other smaller periodicities (in total 8 main so called "modes").

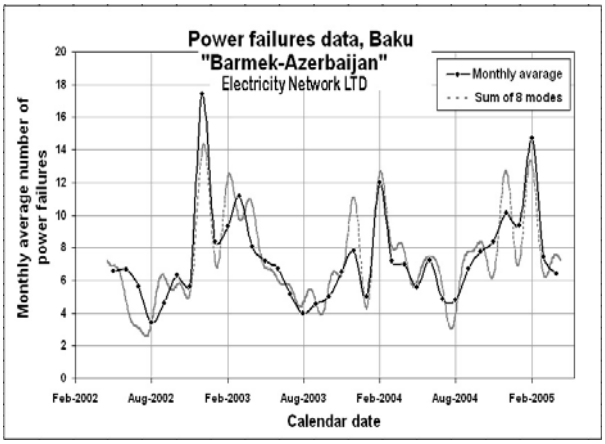

Fig.1. Power supply system failures, Baku data.

Obtained results could be explained by possible influence of variations in solar and geomagnetic activities. Variability in the geomagnetic activity has several sources which includes the variability in the Sun itself that is reflected in the solar wind/interplanetary magnetic field (the 11- and 22-year solar cycles and the 1.3 year variability), the annual variability (the Earth's orbit around the Sun taking it to different helio-latitudes), as well as semi-annual and recurrent (27-day) variations. One of major rhythms in solar-terrestrial system is quasi-2-year in solar and geomagnetic indexes, particularly in solar wind. Besides, 1.97, 1.61, 1.48 year periodicities were found in the lower frequency part of the power spectrum of variations of the mean magnetic field (MMF) of the Sun for 1968-2000 on the base of joint 33-years observations conducted in Crimean AO-Sayan (Irkutsk) - Mount Wilson and Wilcox Solar Observatory (USA) [12].

Our analysis revealed that most vulnerable months for power systems are the end of February and beginning of March as well as autumn months. This agrees with the seasonal dependence of geomagnetic storms and their impact.

It is not only the geoelectric field that dictates the GIC magnitudes in a power system but also the geometrical and structural details, varying resistivity along lines have a significant influence. Our detailed study showed that those transformers, which are positioned at the corners (or at turning points) of an electrical power transmission system, suffer more damage from geomagnetic storm effects.

The direction of power lines is also very significant. The lines in the East-West direction are more influenced than one in the North-South direction; in our opinion, it is due to the fact that the induced electric field goes mainly in an East-West direction. Also, long transmission lines carry larger GIC and a high Earth resistivity makes the geoelectric field values larger.

The most vulnerable areas from the point of view of supply system and transformer failures are Absheron Peninsula with capital city Baku having several millions of inhabitants, Ali-Bayramly region, the area (west-oriented corridor) between two latter, as well as, particularly, Mingachevir region (with very big hydro-electrical power station) and some coastally located "sea-land boundary" areas (probably, the Caspian Sea, as oceans, can conduct electricity easily and can carry large electric currents; when these currents reach shore in Absheron Peninsula, particularly when the crust is nonconductive, voltages can jump into wires and pipelines with potentials measuring hundreds of Volts).

The complex behavior of the internal magnetic field patterns under saturation is a source of internal heating of transformer. Both large geomagnetic storms as well as weaker but repetitive storms can contribute to transformer failure problems. Large storms can cause internal heating damage in a very short period of time. During October-November 2003 storms, some incidents of transformer heating problems were registered by JSC "AzerEnerji". The suspected failure linkage is stray flux impinging on external core structures in concentrations intense enough to develop hot-spots. Weak, but long-duration storms can also cause transformer-heating damage. These extended duration heating insults raise the likelihood of loss-of-life to transformer insulation. This damage can be cumulative and acquired over repeated exposures.

Our investigations have shown that geomagnetic storm effects were not so strong in Azerbaijan and the effects on power consumers were small during weak and mild geomagnetic storms, while they became significant at days with severe geomagnetic storms. But it should also be taken into consideration that significant impacts could be triggered at even lower storm levels and not only late at night and not only during the peak of the sunspot cycle.

It is supposed that, despite of less variation in the peak magnitude of *delta-B*, *magnetospheric shocks* or *storm sudden commencements* due to large scale interplanetary

pressure pulses and caused by them impulsive disturbances followed by large geo-electric field and large GIC flows as well as deep-earth ground conductivity conditions alongside with the design of the power grid might be responsible for low- and mid-latitude power system failures [11].

The interconnectedness, however, can lead to increased vulnerability in some circumstances. When a solar storm damages one system, systems connected to it can experience failure as well, as a chain effect. Enlarging of existing big interconnecting network of electrical supply systems of neighbor countries such as Azerbaijan, Russia, Iran and Georgia makes vulnerable power grids: these kinds of large interconnected power grids have become in effect a large "receiving antenna" to the major geomagnetic storms, GICs and other space weather effects.

By receiving geomagnetic storm alerts and warnings/forecasts, Azerbaijani power supply companies and managers can avoid or minimize possible damages, interruptions to power supplies and power outages, and hence produce cost savings during severe geomagnetic storms.

Geomagnetic storms and their influence on the functional state of the human brain

There is an evidence that the human nervous system is a target and/or messenger at effecting fluctuations of geomagnetic field on human physiological state and, particularly, on human brain's functional state. Investigation of bioelectric activity of the human brain, which reflects a continuum of functional conditions, is an adequate way for study of a condition of cerebral cortex of the big hemispheres and cortico-subcortical interrelations. Therefore, in our research works [13-15] the electroencephalographic (EEG) investigations are used as the most objective research method reflecting functional state of the human brain.

We have studied the possible influence of geomagnetic storms of various strengths on the human brain activity and its functional state.

In our experiments data record of bioelectric activity of the human brain was made with the help of electroencephalograph "*Medicor*", which is a multi-channel (16 channels) recorder intended for registration of the physiological characteristics. The digital data was recorded and subsequently subjected to reviewing and analyzing qualitatively and quantitatively.

Twenty seven healthy female persons (permanent group), aged between twenty and forty years old, selected from the same geographical area, were chosen for a long-term investigations during geomagnetically quiet (favorable) days, at days with weakly-disturbed, and strongly-disturbed (unfavorable) geomagnetic conditions. All female patients were examined in the inter-menstrual period.

Daily changes of meteorological situation during the experiments were taken into account. In order to avoid possible psychological effects prior to experiments, the persons under test were not familiarized about space weather conditions before and during experiments. The experiments were conducted in isolated rooms and in hospital conditions.

Registration of spontaneous EEG by a mono-polar way from sixteen standard leads arranged pursuant to the international system of "10-20" and a parallel registration of the electrocardiogram was conducted. The experiments were carried out in the standard system from forehead (frontal), central, parietal, occipital and temporal areas of both hemispheres of the human brain.

Investigations were carried out for quiet and active awakeners in conditions with open and closed eyes, in the states of relax, in photo-stimulation and in the process of a hyperventilation. The native records of EEG, which were obtained at different functional conditions, relevant data and registered curves, were stored. Later on, after removal of artefact segments, they were subjected to the computer analysis using the relevant software "*Conan*". Spectral and amplitude mapping, correlation and periodical-metric analyses were carried out. Frequency and amplitude cartograms, obtained for different functional conditions, reflect features of the human brain functioning at comparatively quiet days and at days with severe geomagnetic storm.

Experiments were conducted taking into account solar and geomagnetic storms during above-mentioned days in 2001 - 2005. As the most widely-used parameters of the geomagnetic activity for biomedical problems, daily variations of the *Ap*-index and *Dst*-index were used in our researches alongside with other space weather parameters.

Our investigations have revealed an indisposition, weakness and presence of indistinct localized headaches during days with severe geomagnetic storms for the large majority of persons under test while there were almost no significant complaints about functional state in periods of weakly disturbed geomagnetic conditions (only in some cases a weakness was noted).

Analysis of results conducted during the periods of weak geomagnetic disturbances showed shifts, mainly seen in the frequency spectra. Some acceleration of dominating frequency was observed. Groups of synchronic alpha- and theta waves, which had amplitudes slightly exceeding the background and appearing mainly at loading, were bilaterally-synchronically registered at antero-central areas. No pathological activity and paroxysmal phenomenon, including paroxysmal-similar signs, were registered. Inter-zonal distinctions were clearly traced. Reactivity of dominating alpha-rhythm decreased a little bit.

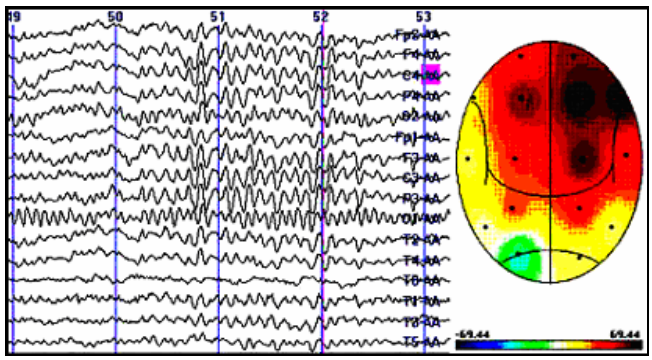

Fig.2. Typical example of total (summary) amplitude cartogram of EEG during severe geomagnetic storm for the whole length of hyperventilation process.

In days with severe geomagnetic storms, a bioelectric activity of the human brain was characterized by reduction of frequencies of dominating rhythm, by amplification

(strengthening) of expressiveness of slow-wave component (mainly a theta-rhythm) and by increase in amplitude of activity (Fig.2). We have observed the forms of waves with pointed outlines and strengthening of process of synchronization of activity.

Flashes of pointed and sharp alpha- and theta-waves, having right cerebral hemisphere's accent (stress), were registered during our experiments. Smoothing of inter-zonal distinctions was observed as well.

During the hyperventilation process, observable flashes of both pointed and sharp alpha- and theta-rhythms were amplified, and their amplitude was increased.

For a part of examinees diffuse synchronization was traced on frequency ranges of alpha1 and alpha2 rhythms. Reactivity of dominating activity was weakened, and reactions of adopting a rhythm were observed on lower frequencies of the alpha-range.

Figure of correlation interrelations, inherent to various functional conditions, was broken. Inter-hemispheric asymmetry was revealed. The leading role in interrelations had temporal area of the right cerebral hemisphere. Activation of rostral-temporal and caudal-temporal connections (links) of the right hemisphere was marked.

The obtained results prove the significant changes in activity of the human brain during the days with severe magnetic storms, reflecting infringement of functions on both central integrative mechanisms and local processes of brain regulation.

It is well known that the most sensitive sections of the human brain, influenced by negative factors of an environment, are hypothalamus (a region in the upper part of the brainstem that acts as a relay to the pituitary gland; it controls body temperature, circadian cycles, sleep, moods, hormonal body processes, hunger, and thirst) and cerebral cortex of the big hemispheres of the human brain. The increase of representativity of theta- and alpha-rhythms carrying flash-like character, testifies on dysfunction of mesodiencephalitic sections within the limits of which hypothalamic nucleus are located. Considering hypothalamus as a leading part of nonspecific systems of the human brain and as responsible for neuroendocrinal and vegetative regulation, it should be noted that strong geomagnetic disturbances infringe normal activity of this structure, causing imbalance in ergo- and tropho-tropic interrelations. In days with weak geomagnetic storms, an order of this dysfunction was low and it was mainly traced at functional loadings, i.e., at transfer of organism from the state of rest to active state.

The dysfunction, registered on EEG at days with severe geomagnetic storms and reflecting ascending sendings of non-specific systems, undoubtedly affects descending directions as well, causing complex vegetative complaints observed in the majority of examinees. At the same time, it must be noted that pointed and sharp flashes of waves of theta- and alpha-range which are observed on some tested persons in the days with severe geomagnetic storms, testify the paroxysmal character of the infringements, specifying on reduction in a threshold of convulsive (spasmodic) readiness mesodiencephalitic formations with followed corresponding clinical-neuropsychological consequences.

Observed right cerebral hemisphere accent (stress) of changes testifies the greater "interest" of right hemisphere. It is established that activation of the right hemisphere is accompanied by negative tinge of emotional reactions. Outgoing from this fact, it is possible to assume that during significant disturbances of geomagnetic conditions the negative emotional background of the person is amplified. This assumption is also proven by results of the correlation analysis specified on strengthening cortical connections in the right cortical hemisphere and their short circuit on temporal sections, while, in geomagnetically quiet days, a profile of correlation interrelations has reflected weak internal- and inter-hemispheric connections.

Thus, results of our researches testify on different character of influence of weak and severe geomagnetic storms on the functional state of the human brain.

During days with weak geomagnetic disturbances no significant changes in the human brain activity were observed. Some negligible shifts, registered for several persons, reflected an increase of activity of mesodiencephalitic structures which is observed at activation of organism.

Comparing to the above mentioned results, in days with severe geomagnetic storms the human brain's activity is seriously disintegrated. Normal functioning of integrative nonspecific systems, located within the limits of limbric-reticular complex and responsible for creation of the corresponding level of wakefulness, which is directed on realization of optimum current activity of an organism, is broken. Imbalance of activating and deactivating mechanisms arises including also dysfunctions of ergo- and tropho-tropic over-segmentary centers.

The threshold of convulsive (spasmodic) readiness of the human brain is reduced which is especially dangerous for the persons of high risk and, as a result, this fact should be taken into account for preventive measures and therapy of paroxysmal conditions.

The obtained results allowed making a conclusion that the strong disturbances of the geomagnetic conditions can negatively affect the human organism, having an effect on functional activity of a brain and changing its background state.

It is established that weak and moderate geomagnetic storms exert stimulating influence while the strong disturbances of the geomagnetic conditions activate braking (inhibiting) processes.

Changes of heliogeophysical conditions and their possible influence on the beekeeping

Biosphere (including animals) is very sensitive to solar and geomagnetic activity and to changes in these activities and their manifestations in the Earth. According the NOAA Space Weather Scale for Geomagnetic Storms animal effects start at a G1 level (with maximum of G5) and these effects are more pronounced as the geomagnetic field is more disturbed.

Since all living organisms are probably affected by magnetic fields, anything that influences those fields (solar activity changes, solar flares, solar wind variations, coronal mass ejections, geomagnetic filed disturbances and/or storms, etc.) will indirectly or even directly perturb living organisms.

Honey bee, *Apis Mellifera*, is known [16] to be sensitive to magnetic fields and its famous "waggle dance" is modified when the Earth's magnetic field is cancelled, which is a strong indication of a highly sensitive magnetic detection system. Studies of honey bees in terms of their "dances" have revealed that the orientation of the dance (indicating direction of good forage) can be in error up to 20% in disturbed geomagnetic conditions. These errors are not "system noises", but are constant with all bees that are dancing at any particular time.

We have studied [17-20] the possible influence of changes of heliogeophysical conditions on the beekeeping, particularly, on the honey yield level and changes of number of honey bee colonies.

For the purposes of studies of possible space weather influence (periodical changes in solar and geomagnetic activities, as well as solar energetic events and caused by these events geomagnetic storms) on honey bees and honey production, we have collected honey yield data from different regions of Azerbaijan with traditions of beekeeping; these regions (spread on longitude and latitude) were grouped taking into account local peculiarities and climatic conditions.

In order to carry out comparison, we have collected relevant data from other countries – close and far regions. We could handle data on total honey yield from Russia, Europe, Canada, and whole world.

Each data from different sites was studied separately and results were used in interpretation. In this paper, a special attention was paid to the analysis of world honey yield data (time span: 1975-2001), which, has reliable statistics and, in our opinion, reflects the possible global space weather impact better than in the case of regions having their own peculiarities making the task more complicated. As Canada is thought to be one of the worst places because of direct and potential influence of space weather conditions (high geographical latitudes, closeness to the magnetic pole where energetic particles can spiral down easily along almost perpendicular geomagnetic force lines, so on) on technological and biological systems, we carefully investigated world honey production and change of number of bee colonies in the case of Canada.

Such space weather parameters as sunspot numbers, solar radio flux at the wavelength of 10.7 cm, sunspot areas, solar flares, solar wind, interplanetary magnetic field, geomagnetic activity indexes, cosmic rays, etc. were involved in our studies. Results of correlation analysis show quite high values, but they are not provided in this paper as in the case of biological systems these kinds of analyses not always give unambiguous picture and require careful approach.

Conducted Fourier analysis has revealed a steady quasi-12-year periodicity in the world data on honey production within the considered time interval (about 27 years which covers almost 2.5 solar activity cycles) (Fig.3). This period is very close to the well-known quasi-11-year periodicity (this an average value, in fact, a length of solar cycle varies between 9 and 12.75 years) in solar activity changes and to the 12.5-year changes found in the geomagnetic disturbance indexes [3]. It should be noted that an observed divergence on the edges of honey production curve in the considered time interval also shows the quasi-periodic nature of curve. Another well pronounced rhythmic changes have periods of quasi-6- and quasi-4-years which are displayed in geomagnetic activity and solar wind changes [3].

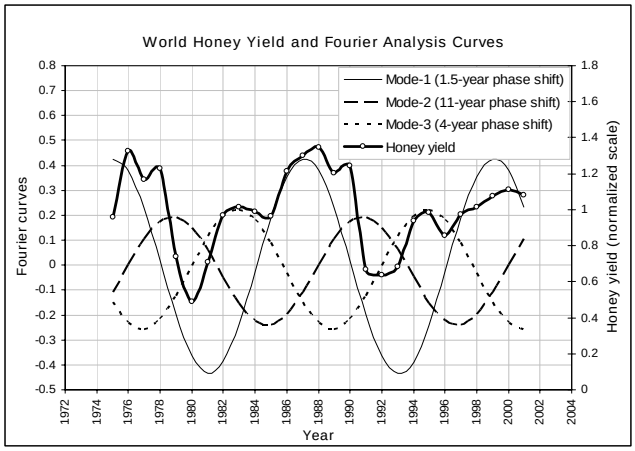

Fig. 3. World honey production and results of relevant Fourier analysis.

For increasing of reliability in the revealing of solar and geomagnetic activity effects on the considered system, the main (with biggest amplitudes) periodical changes were excluded from analysis; major periodical components were first determined, and then, with purposes of decreasing of the above-mentioned multi-factor influence nature of task as much as possible, the obtained dominating quasi-12-year rhythm (hereinafter we will call them as a mode-1 with phase shift of 1.5 year, so on) was excluded from the initial data series. Next step was an excluding of next established quasi-12-year periodicity with 11-year phase shift from the last obtained "clean" data series (mode-2), and so on. The difference between 11-year (mode-1) and 1.5 year (mode-2) shifts is equal to 9.5-year. This value is known to be one of existing periods in solar activity alongside with other well-known values [3].

It seems that this first peak of geomagnetic activity (2-3 years before solar maximum) causes stimulating effects to honey bees, making them an agile while the second peak impacts negatively honey bees resulting in the honey production level decrease. As a result, ascending and descending phases of solar 11-year activity exert different influence upon the honey yield and bees, which is connected to the physical nature of these phases.

There is some kind of impression that each impulse (rise) of geomagnetic activity gives a jerk leading to the increase of honey production with inertia of 1-2 years. Relatively small amplitude geomagnetic activity gives more significant rise in honey production curve (more probably, because of stimulating effect of geomagnetic disturbances to honey bees) while stronger disturbances lead to smaller increase in yield (negative impact of severe geomagnetic conditions to biological systems).

Honeybees are social insects that live in a colony, in large hives, each of which has a single queen, together with workers and drones. Changes of average number of honey bee colonies per apiary per year were also investigated in the base of Canadian database. Results of Fourier analysis show that changes in this number have a periodicity of quasi-12-year. Number of honey bee colonies per apiary follows well

the solar cycle variations; this number increases in the years of solar maximum which is probably related to the honey bee's physiology.

We suppose that geomagnetic disturbances influence bees through magneto-reception mechanism. Some animals possess a specialized set of neurological receptors containing tiny crystals of magnetite, which allow them to "sense" and navigate by the geomagnetic field

It has been found [21] that bees also have magnetite – nano-scale-sized transversely oriented ferrimagnetic material (mineral) with chemical formula Fe_3O_4 (magnetic receptors linked in with their nervous systems) in front of their abdomens (relatively "large" magnetite particles with a size larger than 30 nm) - in trophocyte cells, a specific cell type of the fat body of insects - on one hand, and probably, smaller ones (with a size comparable with ferritin cores) on heads and thoraxes of bees on the other hand, which can be affected even by weak geomagnetic field fluctuations, considered as "noise".

Presence of supermagnetic particles isolated from magnetite such as that found in honey bee abdomens allows responding rapidly to magnetic field variations during a honey bee's flight. The magnetic moment apparently develops in the pupal state and persists in the adult bees. In the absence of all other cues, bees seem to set their circadian rhythms by regular daily variations in the geomagnetic field; an abnormally strong field disrupts the rhythm.

Based on the theory of phase transition induced by the noise and applied in biology, in our researches we consider the honey bees as a biological object acting as an open non-linear system being in the state of non-stable dynamic balance. Transition of this system into another state ("critical" or "disrupted rhythmical") can happen even in the case of very weak external influence having a level of noise and acting as failure of rhythm. Any changes of natural electromagnetic field (geomagnetic field) caused by solar sources can play a role of one of these external factors. Depending on the strength or level of external influence factor, bees react differently which is, in turn, reflected in honey production. As honey colonies as a rule are located in the country areas, far from urban area and sources of technological "noise", their effects are less than space weather effects.

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