CUMULATIVE NATURE OF EXTREMAL EVENTS OF SPACE WEATHER

V.I. Kozlov, G.F. Krymsky

Yu. G. Shafer Institute of Cosmophysical Research and Aeronomy SD RAS,
Yakutsk, Russia, cosmoprognoz@mail.ru

ABSTRACT

By us are revealed the "transition regime" in the vicinity of the front of a large-scale solar wind disturbance by research the "group" features of the behavior of high-energy cosmic rays. The probabilistic identification of the transition regime near the front of the interplanetary shock wave is presented (http://www.forshock.ru/pred.html). Indications are obtained of the important role of the process of nonlinear dynamics of large-scale oscillations of the heliospheric current sheet (HCS) after a series of coronal mass ejections (CMEs) during the active phase of the solar cycle. It is possible that the nature of the most extreme events of Cosmic weather has a common, cumulative origin: as a result of the interaction of “catching up” (in an environment with “time from time” decreasing density) shock waves. This is confirmed by data from direct observations of the interaction of shock waves (after series CME) on spacecrafts.

INTRODUCTION

As is known, in the diffusion approximation, fast particles are assigned individual random trajectories that are not related to each other. At the same time, on small space-time scales, there should be a significant correlation of trajectories, as a result of which groups of particles that are close in phase space remain relatively long time as compact formations with a “single” trajectory. The group behavior of particles is of great interest from various points of view. First of all, it is important when studying the nonlinear interaction of cosmic rays with the environment, as well as for the diagnosis of large-scale processes in cosmic plasma [1].

The aim of the work is to study the transient regime in the vicinity of the front of a large-scale solar wind perturbation to study the features of cosmic ray fluctuations caused by group or correlated behavior of galactic cosmic rays (GCR). Separating correlated fluctuations or “beams” of cosmic ray particles from Gaussian “noise” would allow them to be used as precursors to large-scale perturbations of the solar wind. Correlated fluctuations It is advisable to look for in situations when “colored” groups of particles appear, for the evolution of which is easy to follow. It is known that the greatest contrasts in cosmic rays create shock waves, generating sharp decreases in the intensity of GCRs called "Forbush effects"[1].

Other possible sources of Forbush effects (for example, recurrent perturbations or “streams” of the solar wind, etc.) cause a decrease in the intensity of cosmic rays of much smaller amplitude. In the absence of sporadic (flare) activity, the "jets" of the solar wind can also have precursors in cosmic rays, but this only happens when sufficient gradients are reached in the solar wind parameters at the fronts of different-speeds jet. In the general case, it is impossible “a priori” to distinguish precursors from flare shock waves from precursors at the boundary of different-speeds jet of solar wind.

In another type of solar wind disturbance, in piston waves, in piston waves, the relative compression of matter and field between the fronts exceeds the values it reaches in the body of blast waves. As calculations [2–4] show, in the region between the front and rear shock fronts of such waves, the magnetic field can be subjected to additional amplification of a considerable magnitude. Therefore, we can speak of a magnetic "traffic jam" in the vicinity of the shock wave front propagating along with the unperturbed solar wind. The presence of similar magnetic cork in shock wave generates the separation of particle trajectories into "allowed" and "forbidden". The former connect the regions in front of and behind the shock front, and the latter isolate these regions from each other [5–7].

As a result, in the vicinity of magnetic traffic jams, a different kind of deformation of the phase volume will occur: an alternation of regions of different density will occur "intermittency" will appear. In the angular distribution, which is a two-dimensional projection of the distribution function, we should expect the appearance of clusters, the size and contrast of which should decrease with distance from the source. In this case, observations of the angular distribution should show the "flickering" of the celestial sphere in cosmic rays, the properties of which depend on the source: on the characteristics of the magnetic field and on the distance to the observation point. It can be expected that the parameters of cosmic ray scintillations will have fractal properties [6].

ABOUT THE PRINCIPAL POSSIBILITY OF FORECASTING SOLAR ACTIVITY

It is known that the fractal properties of the process are determined by estimating the fractal or correlation dimension of the process. The finite dimension d means that this signal can, in principle, be recreated using a dynamic system of order not higher than 2d + 1 [8]. Moreover, it can be argued that the dimension of the process correlates with the number of structures (or modes) interacting with each other. And, conversely, with a finite and low value of the correlation dimension is finite and the number of modes, which corresponds to a more deterministic process structure [9].

Investigation of the statistical distribution of the number of Forbush lows with amplitudes A>1.5% in the SA cycle according by data of the neutron monitor of st. Alert conducted by the authors of [10] showed that a maximum of distribution of the number eff. Forbush is correspond to the onset of the declining branch of solar activity. This is most likely the reason for quite sharp decreases in the 27-day GCR intensity values at the beginning of the descending branch of the 11-year cycle. It is known that coronal mass ejections (CME) are a source of shock waves and magnetic clouds. Their number also increases at the beginning of the descending branch of the 11-year cycle [11].

In this regard, it should be noted that “reaching a plateau” of the usually monotonous d (n) ~ n dependence of the correlation dimension on the phase space dimension n occurs when the correlation dimension reaches d = 2.5-3 [12-13]. In relation to the task of predicting solar activity, the very fact of detecting low-dimensional, i.e. partially determined process in the active phase of the 11-year solar cycle serves as a kind of "existence theorem", ie an indication of the fundamental possibility of predicting the geoeffective phase of the beginning of the decay branch of the solar cycle, where the probability of serial events is high.

EXTREME EVENT OF SPACE WEATHER - AS A MANIFESTATION OF THE STATE OF “SELF-ORGANIZED CRITICITY”

The choice of methodology for studying of the transition regime to the extremely active phase of the solar cycle was determined by the following results. By the hourly intensity values of the GCR of st. Oulu (Finland) for 45 years from 1968-2012 was determined the number of events (decreases in the GCR intensity) of a fixed amplitude. Thus, the distribution of the numbers of events depending on their amplitude was revealed (Fig. 1). This is consistent with the result obtained earlier in [14], which is confirmed by the proximity of degree exponent τ: “-1.60” for X-ray flashes and “-1.56” in cosmic rays. Inverse of dependence usually indicates the absence of a distinguished or “characteristic” scale of the phenomenon: i.e. there is a hierarchy of scales, which indicates the self-similar or fractal nature of the process as a whole. This is consistent with the final and low (d=2.5-3) value of the correlation (fractal) dimension of the process on the active phase of the solar cycle [13]. Indeed, the plausibility of the obtained estimate of the power exponent τ clearly follows from the analytical expression of his relationship with the fractal dimension: $d=\tau+1$. The absence of the “characteristic” scale of the phenomenon means that the number of any arbitrarily taken events on the Sun will always be more than the number of more powerful events in comparison with them. X-ray events reflect activity at the source on the Sun, and events in cosmic rays reflect the manifestation of the same activity in the upper solar corona and further in the interplanetary medium.

The fact of the existence of an inverse power dependence (with the exponent $\tau<2$) indicates that the dynamic system is in a nontrivial state of “self-organized criticality”, when very irregular, i.e. catastrophically (which significantly complicates the forecast), is “released” the excess energy stored in the system. When $\tau\leq3$, the power distribution has infinite variance, i.e. it makes no sense to try to characterize the deviation of the values of a random variable from its mathematic expectation, and when $\tau\leq2$, the expectation itself becomes infinite. In this case, the sum of the values of a random variable in some sample turns out to be comparable with the largest of them. As a result, both characteristics increase rapidly and unlimitedly as the sample size increases, which provides a typical example of the **anti**-intuitive behavior of scale-invariant (fractal) systems [15-17].

This indicates that the nature of the process is clearly **not** Gaussian, allowing correlations on the arbitrarily large space time scales. As noted in [18], “Long-range correlation effects are manifested in the“ strange ”(non-Gaussian) behavior of kinetic processes ...” and, further: “We can say that strangeness and fractality are mutually agreed characteristics of the same phenomenon - "*self-organization*" of the system to a *non-equilibrium* turbulent state, the dynamics of which are entirely subordinate to multiscale correlation interactions." Therefore, the analysis of “**tails**”, i.e. higher moments of the function distribution which can be quite informative in the problem of detecting the **transition** regime in the vicinity of the shock front.

In particular, by monitoring the state of the environment by cosmic rays with the aim of early detection of already occurred "catastrophe" (in our case - the shock wave) in the interplanetary medium at a distance from the Earth equal to the path length of cosmic rays. This obliges us, figuratively speaking, to constantly "keep our finger on the pulse". Awareness of this and determined the need to develop and create a system for ground-based monitoring of cosmic rays in the Polar Geocosmophysical Observatory Tixie (PGO Tixie) as far back as 1981. Below, an approach is proposed that to some extent solves the problem of “forecasting”, more precisely, the early detection of geoeffective events of the Space weather.

The proposed method compares favorably with ease of implementation and efficiency, because it uses the existing global network of ground-based cosmic ray stations - high-latitude neutron monitors, and efficiency. The efficiency of the method lies in the fact that the speed of detection of explosive shock waves from solar flares is almost instantaneous, since cosmic rays registered by ground stations move practically at light speed. In this case, the distance, or "path length" of cosmic ray particles, starting from which ground-based cosmic ray stations record flicker (correlated fluctuations) of cosmic rays from the approaching front of the interplanetary disturbance, is at least 10 times the distance from the Earth to location (for example) of SOHO - USA spacecraft at the "libration point."

For this reason, the lead time for detecting with use cosmic rays a powerful and therefore most dangerous radiation and electromagnetic storm is more than 10 times (≈1 day) more than the lead time achieved on the spacecraft (≈15 min). The economic efficiency of the proposed remote method for early detection of flash shock waves speaks for itself. The cost and operation of, for example, the American satellite system for their forecast is about ~ $ 1 billion. Damage from all kinds of losses associated with missing this kind "space tsunamis" is an equally significant amount.

The ever-increasing dependence of modern civilization on high-tech life support systems in space, in air and on Earth makes us, in fact, hostages of scientific and technological progress based, in particular, on satellite technologies, primarily exposed to the destructive effects of extreme manifestations of space weather. All this indicates the urgency of the problem of early detection of a radiation storm, accompanied by an electromagnetic storm.

IDENTIFICATION OF TRANSITION REGIME IN THE AREA FRONT OF A SHOCK

From the probabilistic theory of continuous medium destruction and reliability theory, it is known that the generalized Weibull-Gnedenko distribution function describes output of the system on a critical or limit regime [19]. In our case, this can be considered as a transitional mode of reaching the active phase of the 11-year cycle or to the vicinity of the interplanetary shock wave. In the language of probabilistic theory, the task of studying the transition regime is reduced to the problem of determining the function of the failure rate of a system that has exhausted its resources. The maximum of the failure rate function, or the maximum of the Risk function, is, in fact, the PROBABILITY of reaching the critical value of the analyzed variable, in this case, the cosmic ray intensity. The ratio of the density of the Weibull distribution function to its “complement” or “reliability function” (Appendix 1) is the desired probability (the Risk function) or the PARAMETER of cosmic ray fluctuations [20]. In meaning, this is an indicator of the degree of correlation of cosmic ray fluctuations, in our case, in the vicinity of the front of a large-scale perturbation.

To calculate the probability of cosmic-ray intensity reaching a critical value on the transitional regime, it will be necessary to evaluate the shape parameter of the Weibull empirical distribution, which determines the degree of deviation of the shape of the approximating function of the empirical histogram from normal distribution. The approximating function of the empirical (integral) intensity histogram is found by the least squares method. The average values of the intensity for each bin interval of the empirical distribution function (integral histogram) will be grouped in the vicinity of the fitted line, but in a new coordinate grid (after the double logarithm procedure and variable replacement). In this case, tangent of the slope angle of straight line, selected by the least squares method and the free term give the ratios needed to estimate the desired shape parameter and scale parameter. The shape parameter is a key parameter: when it reaches a critical value, the value of the parameter is determined as a harbinger of reaching the critical (transitional) mode. The scale parameter - is simply the average value of the GCR intensity for each time interval-bin.

Further, it remains only to isolate the precursor signal from the Gaussian noise: Gaussian noise is contained, simply put, in the “pre-critical” “linear” region of the Risk function, and the sought for signal-precursor is in the critical nonlinear region. The desired nonlinear component of the precursor signal is formed when the probability of the critical value of the analyzed variable is exceeded, i.e. at P>Pкр. TESTING the proposed method on the control series, which is a random numbers, showed that the probability values (further, the parameter of fluctuations) those lying below the level of $P \leq 0.65$ can be reliably (at a significance level of 90%) attributed to Gaussian noise [18].

Calibration of "zero" can be done and according to real data. For this purpose, based on our earlier experience in monitoring cosmic rays at the Tixie Observatory, we have created the Cyber-FORSHOCK robotic expert system for diagnosing and forecasting Space Weather. It is best to calibrate the “zero” of the GCR fluctuation parameter at the minimum phase of the 11-year cycle, when flare activity is minimal (Fig. 2). It is important to note that the character of “Cosmic Noise” during this period is clearly chaotic. Obviously, this is due to the chaotic nature of the radiation background of galactic cosmic rays, which was dominant at that time, due to a decrease in solar activity during the minimum of the solar cycle: the dependence of the correlation (fractal) dimension on the dimension of the enclosed phase space during the minimum of the 11-year cycle is typical for random process with monotonic dependence $d(n) \sim n$ [20].

The necessary operation to suppress the cosmic “noise” is the procedure for supplying to the analyzer input, along with the initial signal, two versions of the “out-of-phase” initial signal, with the output on this unit being the average value of their sum. Moreover, the value of the time shift (± 1 hour) of both "out-of-phase" signals is much smaller than the averaging interval of the fluctuation parameter (12 hours). This procedure (due to mutual suppression during the summation of the random component of the signals) made it possible to almost halve the variance of the initial time series.

With aim to eliminate the situation of “missing a target” (known in radiophysics as “1st kind error”), as well as cases of registration of non-geoeffective Space weather events, in fact - “false alarms” (“2nd kind errors”), was made adaptation of the created by us the robotic expert system “Cyber-FORSHOCK” to the detection of geoeffective events of the Space weather. For this, a combination of two blocks was used: a “noise suppression” block and a “frequency range extension” block of cosmic ray variations. The block for expanding the frequency range includes the use of polynomials in the trend exclusion procedure not only of the 2nd, but also of the 3rd order, “simultaneously”. Using polynomials of the 2nd and 3rd order allows us to expand the frequency range of the remaining (after subtracting the trend) small-scale variations.

ABOUT CUMULATIVE NATURE OF EXTREME EVENTS OF SPACE WEATHER

An illustration of the work of the proposed method on the example of known events in October 2003 is shown in Fig. 3. In addition to the extreme decrease in GCR intensity on October 28-31, 2003, during the period under review, 2 events of average magnitude were also recorded: October 21-22 and October 24-25. All three events, in the fluctuation parameter, are preceded by significant (at the 95% level) values of the GCR fluctuation parameter, i.e. - harbingers: October 20, October 23 and October 26-27. The precursor of October 20 reflects the beginning of the rapid growth of Active Region No. 484. At the time of the appearance of this area, due to the eastern edge of the solar disk on October 18, 2003, it was barely noticeable, but starting from the next day on October 19, its rapid activation began: On October 20, large flashes of class M1 and X1 were recorded

The harbinger on October 23 could be attributed to the rapid activation of the same source (AO No. 484), but could not be ruled out contribution and from the reappeared the more powerful active area 486: in this active area on October 23 was recorded a large flare, X5 class. Subsequent low values of the fluctuation parameter on October 21, 24, and October 28–30, state the fact of diagnostics of predicted events, i.e. registration Forbush effects in GCR intensity. The giant decrease in GCL intensity on October 28-30 (as well as the previous decrease on October 24-25) is most likely due to the cumulative effect in the magnetoplasma current sheet, i.e. heliospheric current layer (HCS) after series of powerful releases of the coronal mass (CME) due to large and very large flashes in the analyzed period of class M1-M7 and X10-X17.

The research of the dynamics of the GCR fluctuation parameter in October 2003 is carried out using wavelet analysis. To do this, consider all events in general, in particular, for the period from 10.16.2003 - 11.11.2003, by data one station Tixie. As a result, indications were obtained on the important role of the process of nonlinear growth amplitude of quasi-week oscillating: oscillating with a period of ≈4 days was transformed into a variation of larger amplitude, but with a smaller period of ≈2 days (Fig. 4). The conclusion about the "oscillations" follows from the "monochromatic" properties of oscillation: oscillation is highlighted in color in the chart of periods. Moreover, with a clear trend to the high-frequency region: there is a systematic shift of the period of variation towards shorter periods (from 4 to 2 days). And so, right up to the moment of the splitting of the spectral "line" of oscillations, which is clearly visible both by the dynamic of spectrum over time and on the graph of the global spectrum as a whole for the entire analyzed period (Fig. 4). As a result, the process ends with the registration of a shock wave with extreme power (Appendix 2a-e).

In serial events, similar to extreme events in October-November 2003, it is rather difficult, if not impossible, to identify the dominant source of activity: at this time, 3 powerful active regions were registered on the visible part of the solar disk (nos. 484, 486 and 488).). In such cases, the decisive role is played by nonlinear effects, which lead to abrupt growth of the amplitude of oscillations of the HCS - an analogue of the "cosmic tsunami" in the Earth's orbit.

The largest amplitude (since the beginning of the 21st century) of decrease in the GCR intensity on October 28-30, 2003 is accompanied by a no less extreme radiation storm and a SUPER storm. This is confirmed by the registration in the third decade of October 2003 of a significant flux of storm particles in a wide energy range (including protons with energies of ~ 1 MeV) according to measurements on the ACE American spacecraft, with the maximum flux immediately before the Forbush effect 28- October 30, 2003 (Appendix 2e). The vertical arrows show the location of the precursors. It can be seen that the harbingers precede all five increases in low-energy particles, including for a relatively small event on October 5 2003. At this time (October 5-6), the Earth entered a high-speed stream of the solar wind from a coronal hole. This is a good illustration of the fact that harbingers are recorded both in front of blast shock waves and in front of high-speed streams or jets of the solar wind.

Noteworthy is the registration on November 3 of a significant (at the level of 99%) harbinger before a giant X-ray flash of class ≥X28 that occurred on November 4, i.e. at the moment when the source of activity approaches the western edge of the solar disk (Fig. 5): http://spaceweather.com/archive.php?view=1&day=04&month=11&year=2003. And only the location of the source did not allow it to manifest noticeably on Earth. However, 2-3 days after the giant flare on November 4, on November 6-7 a slight decrease in the GCR intensity was registered in cosmic rays, which is confirmed by a markedly reduced, i.e. diagnostic value of the GCR fluctuation parameter (Fig. 5). Thus, simultaneous registration of 6-7.11.2003 a decrease in the intensity of the GCR and the reduced diagnostic value of the parameter of fluctuations is a kind of marker of a powerful, but not so geoeffective, source of activity.

Nevertheless, the activity potential of all three active regions was preserved: http://spaceweather.com/archive.php?day=12&month=11&year=2003&view=view. It was reported on the continuing activity of the above sources, accompanied by a series of CMEs: November 6, 7, 9, 11-12 and 13. Obviously, the cumulative effect of mass emissions of CMEs manifested itself in the registration of a precursor in cosmic rays on November 9-10 (Fig. 5), i.e. before the release of the source of activity on the visible part of the solar disk. No other obvious sources of activity were found: the surface of the Sun was practically without any spots. The registration of the low value of the cosmic ray fluctuation parameter on November 14-15 obviously reflects the result of diagnostics of a large-scale perturbation of the solar wind in the Earth’s orbit. On the other hand, one cannot completely exclude the possible contribution of the high-speed flow of solar wind at this time. The next harbinger on November 18 was registered a day before the start of the SUPER-storm on November 20 (ibid., Fig. 6). The SUPER-storm on November 20 is most likely also of a cumulative nature, i.e. is the result of the interaction of shock waves after (http://spaceweather.com/archive.php?day=19&month=11&year=2003&view=view) a series of CMEs from all three AOs: 484, 486 and 488.

An equally striking case confirming the cumulative nature of extreme weather events can be a SUPER-storm on November 7–9, 2004. In the interval from November 3–10, class M and X flares were recorded, accompanied by a series (about 10) of powerful coronal mass ejections - CMEs. If the first harbinger (October 31 - November 1, 2004) is difficult to attribute specifically to AO (No. 691, 693 or 696), then the harbinger of November 6 (Fig. 6) can definitely be attributed to practically the only source (AO 696). Unlike the events in October-November 2003 (when 3 powerful active regions were observed), in the events of the first ten days of November 2004 one source dominated - AR 696: at least 3 class X outbreaks were recorded, accompanied by a series of powerful CME [21]. The complex nature of the interacting shock waves in the Earth's orbit was manifested in the registration of a stream of storm particles from tens of KeV to tens of MeV on November 7 and 9 and the subsequent two-stage Forbush effect on November 7–10, 2004 with amplitude 7-8 %, accompanied by a SUPER-storm on November 7–10.

It is likely that the nature of all three SUPER-storms on October 30-31 and November 20, 2003, and also November 7-9, 2004, has a common, cumulative origin: as a result of the interaction of shock waves that catch up of each other (in a medium with a decreasing "time after time", density). In this case, it hardly makes sense to look for that "only" gigantic flare, which could be lead to any (from mentioned above) of the extreme Space Weather events.

No less favorable conditions for identifying the source of activity on the Sun were formed in June 2012: the recurrent "jet" of the solar wind dominated only in early June. Its passage was manifested in cosmic rays in recording low values of the fluctuation parameter in the first week of June. Registration of significant precursors on June 10 and 13, 2012 (Fig. 7) occurred at the time of the active region 1504 exit on the eastern part of the solar disk, accompanied by M-class flares, which ended on June 13 with the ejection of the coronal mass of CMEs. The start of the release of (https://spaceweather.com/archive.php?day=14&month=06&year=2012&view=view) the repeated CME was recorded on the following day - June 14 (Appendix 3). The arrival of the shock wave into the Earth's orbit manifested itself in cosmic rays as a low value in the GCR fluctuation parameter on June 16, simultaneously with the registration of the Forbush effect (Fig. 7). This is confirmed by the results of modeling conducted by Goddard Space Weather Lab according to direct measurements on US spacecraft (Appendix 4). This simultaneously indicates good diagnostic capabilities of the GCR fluctuation parameter: low parameter values play the role of a reliable marker for registering a shock wave in the Earth's orbit.

A SUPER storm was also recorded on June 22-23, 2015: http://wdc.kugi.kyoto-u.ac.jp/dst_provisional/201506/index.html. No less powerful was the Forbush effect from June 21–23, the harbinger of which was recorded on June 18, 2015 (Fig. 8). As in previous events, the grandeur of this event is most likely due to the same cumulative effect of the interaction of overtaking shock waves from the CME series, caused by a series of large flashes: class M1, M3 (https://spaceweather.com/archive.php?day=21&month=06&year=2015&view=view) and M6, from June 20-22. Clearly, this can be seen from the results of model calculations (Appendix 5) conducted at the Goddard Space Weather Lab according to measurements on the Stereo-A and Stereo-B spacecraft for June 22. The earth is indicated to the right of the disk of the Sun by a circle on the horizontal axis. And in this case, low values of the GCR fluctuation parameter on June 22 (Fig. 8) are a marker recording the arrival of a shock wave into the Earth's orbit. Similarly to what was previously shown for similar interaction of the CME pair in the event of June 15-16, 2012 (see Appendices 3-4). The conclusion obtained in this work on the important role of the cumulative effect of a series of (catching up) shock waves is confirmed by direct observations of the interaction of shock waves from a series of CMEs on spacecraft in June 2012 [22].

A similar situation developed in early September 2017: on September 2-3, 2017, a significant harbinger was registered (Fig. 9), which is obviously associated with a literally "explosive" (within 24 hours) increase in the activity of source No. 2673 that reached the central meridian Suns: September 4-5, 2 large flares of class M4 and M5 were recorded, which were accompanied by two coronal mass ejections. Literally the next day, September 6, 2017, AO 2673 (https://spaceweather.com/archive.php?day=06&month=09&year=2017&view=view) was the source of a powerful x-ray flash of class X9, with a no less powerful emission of CME. In accordance with the conclusions of the authors of [23], a more powerful release of September 6, catching up with the previous two, formed a complex magnetoplasma formation (Appendix 6), which caused a large magnetic storm (Kp≈8) and the two-stage Forbush effect (September 7-9) ≈10%).

The propagation of shock waves (in a medium with decreasing density "time after time") obviously leads to the cumulative effect of amplification of shock waves in the Earth's orbit and the subsequent extreme event in space weather: to a significant flux of so-called storm particles in a wide energy range (from tens of KeV to tens of MeV) and a large geomagnetic storm. A good illustration of what has been said is the SUPER-storm March 13-15, 1989, known as the "Quebec" (Canada) event. And in this case, the harbinger in cosmic rays was recorded at the stage of the exit of the active region (No. 5395) on March 6, 1989 to the visible part of the solar disk (Fig. 10). The entire period of passage of this AO, from the moment of its release and further, was accompanied by a series of powerful x-ray flares (class X). Significant precursors were recorded on March 9–10, immediately before the start of the giant Forbush effect, March 12–17, 1989.

In this regard, the nature of the unique SUPER storm April 11-12 is interesting. It seems that, in this case, the "cumulative" effect catching up (in the environment "decreasing density of the medium over and over again") played a decisive role each other's shock waves or the "cannibalistic combination" (https://spaceweather.com/archive.php?view=1&day=11&month=04&year=2001) of a pair of CMEs. The harbinger in cosmic rays was recorded on April 10 (Fig. 11), from flares of class M and X2, accompanied by a pair of powerful ejections of the coronal mass CME of the halo type: https://spaceweather.com/archive.php?day=10&month=04&year=2001&view=view. On April 10–11, low-energy flows of “storm” particles with energies from tens to hundreds of MeV were also recorded. All this ended with a powerful flash of SCR on April 15 in a very wide energy range: from tens of MeV to SCR of high energies (Fig. 11), which is confirmed by the data of the global network of neutron monitors. The high density of events in the studied monthly time interval makes it possible to obtain a plausible estimate of the effectiveness of the detection of extreme Cosmic Weather events with a probability of at least 80%.

CONCLUSION

Above, the self-similarity or fractal nature of the magnetic field on the transitional regimes of the solar wind has been noted. This is indicated both by the power-law nature of the dependence of the number of intensity decreases on their amplitude (see Section 2), and the low and final (d=2.5-3) value of the correlation (fractal) dimension of process at the geoeffective phase of beginning of the decline branch of 11-year cycle [12-13].

Generally speaking, the trajectories of cosmic rays in fractal magnetic fields differ significantly from the Brownian trajectories. This means that the change in the function depends not only on its values in the vicinity of the point in question (as is the case with normal diffusion), but also on its values at remote points in space [25]. These non-local processes include non-Markov processes, i.e. processes with "memory" when increments cannot be considered stationary. In this case, we are dealing with the “fractal Brownian motion” [25].

Thus, the non-local features of the behavior of cosmic rays in the vicinity of a large-scale perturbation (shock wave) with the fractal properties of a magnetized medium occur in both space and time. Obviously, it can be concluded that the non-locality of cosmic rays in the vicinity of a magnetic “plug” on a shock wave is caused by the fractal of a magnetized medium in a state of “self-organized criticality”: in this is the physical essence of the transition regime in the vicinity of the front of a large-scale solar wind disturbance - shock wave.

At the non-locality and non-linearity of the processes, especially in the case of powerful events on the Sun, was pointed out in [26]: "... the presence of a direct energy cascade means a strong delocalization of the area energy-carrying ". And further: "the difference between the situational approach and the event-based approach essentially consists in the need to consider account longer time intervals and larger areas in space on the Sun and in the heliosphere ..." [26]. A similar as a matter of fact statement about non-locality was put forward earlier by M.Gnevyshev, it is noted in [27]: "... physically related solar processes need not necessarily occur simultaneously".

RESULTS

1. Trajectories of cosmic rays in perturbed fractal magnetic fields differ significantly from Brownian trajectories of ordinary diffusion, which determines the nonlocal properties of cosmic rays in a fractal magnetized medium in the vicinity of the front of a large-scale perturbation of the solar wind - the shock wave.

2. The nonlocality of cosmic rays is manifested in the clustering of the phase volume of cosmic rays: registration of correlated fluctuations in the form of particle beams - the "halo" effect in cosmic rays in the vicinity of the front of an interplanetary shock wave.

3. It is shown that high, significant (above 90%) values of the GCR fluctuation parameter is a probabilistic indicator of the transition regime in the vicinity of the shock front, in fact, a precursor of the shock wave. The value of advance registration of the harbinger is about 1 day.

4. On the contrary, low diagnostic values of the fluctuation parameter are a marker of recording the arrival of a shock wave into the Earth's orbit. This is confirmed by model calculations performed by Goddard Space Weather Lab from measurements on the Stereo-A and Stereo-B spacecraft.

5. It is very likely that the nature of the extreme events of Cosmic weather has a common, cumulative origin: as a result of the interaction of "catching up" (in an environment with decreasing "time after time" density) shock waves. This is confirmed by data from direct observations of the interaction of shock waves from the CME series on spacecraft [22].

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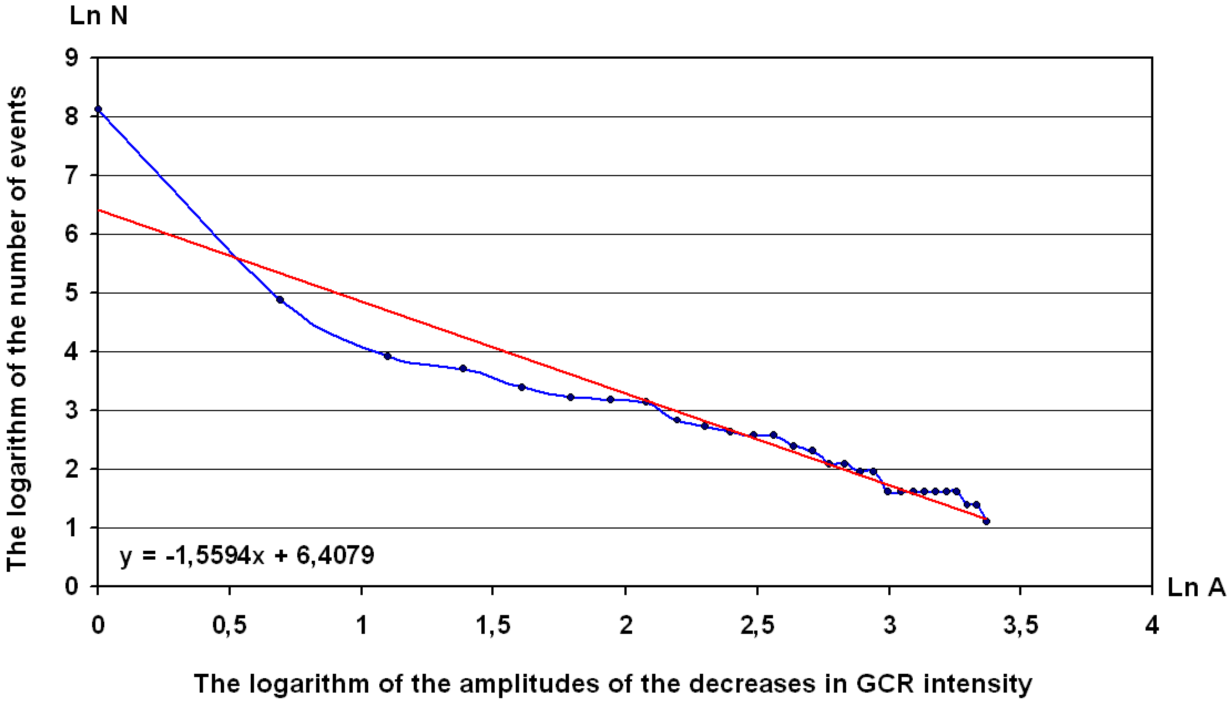


Fig. 1. The degree law of the dependence of the number of events (the decreases in GCR intensity) from their amplitude, by the hourly data of station Oulu (Finland) for the period in during 45 years from **1968-2012**. On the ordinate are the natural logarithms of the number of events, along the abscissa - the natural logarithms of the amplitudes of the corresponding events. "Event" is a decrease in the intensity of the GCR in percent. The value of the index exponent τ: **"-1.56**". Forbush decreases for the indicated period were used in the analysis, starting with decrease amplitude of 1%.

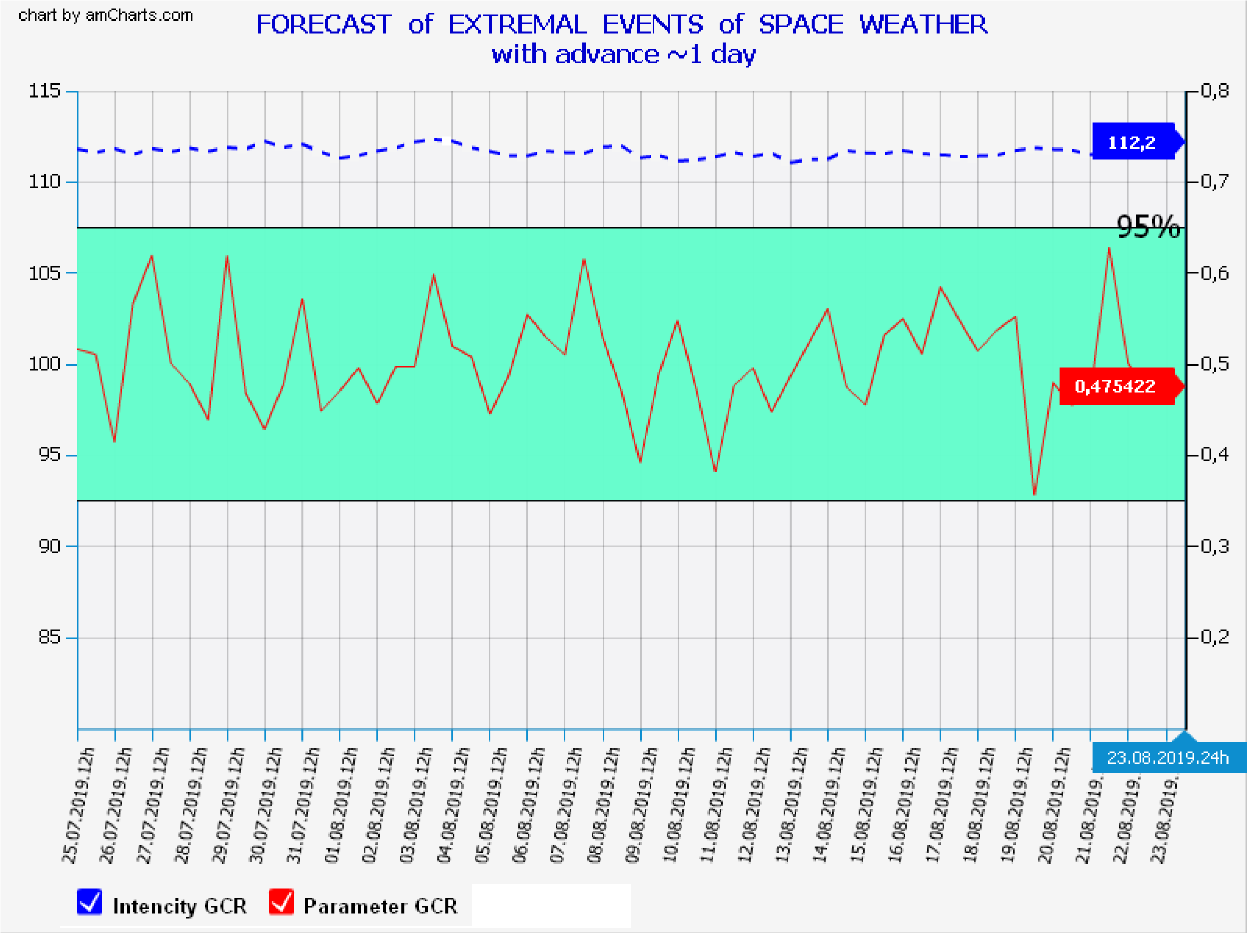


Fig. 2. Results of testing the algorithm for calculating the probability or parameter of cosmic ray fluctuations with 25 July – 23 August **2019** according to **real** data from 12 high-latitude cosmic ray stations from the European database (http://www.nmdb.eu) during phase of **minimum** the cycle 24 by means of a robotic expert system: http://www.forshock.ru/pred.html Cyber-FORSHOCK. On the ordinate axis: the scale on the right (solid curve) - values of probability or fluctuation parameter; scale on the left (dashed curve) - the count speed in pulses for 5 minutes (averaged over 12 hours) by data of the neutron monitor of the Oulu station (Finland). The parameter values are enclosed in the interval: 0.35 <P <0.65 - the "Space noise" area. The abscissa is the date: year - month - day - hour.

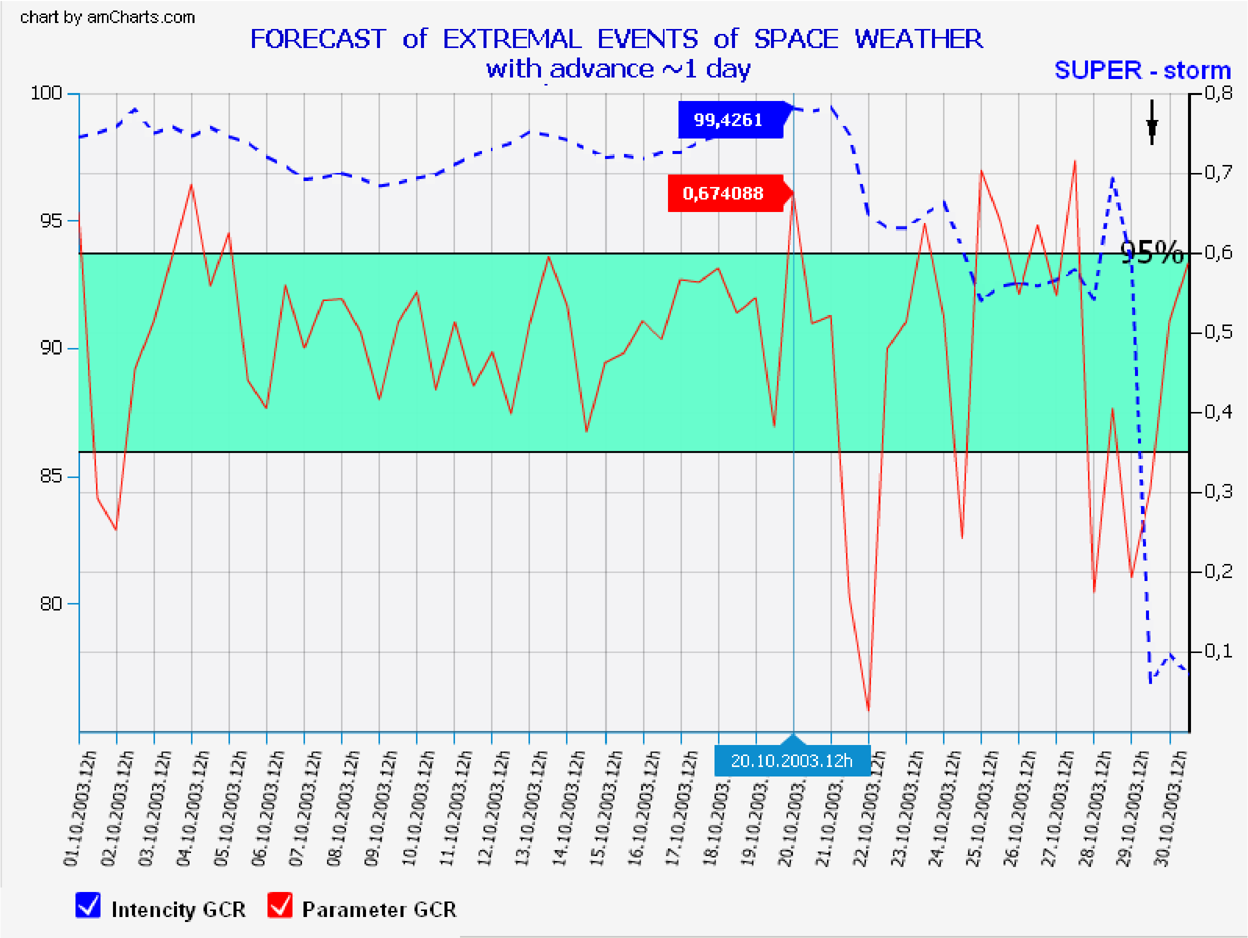


Fig. 3. Results of fluctuation parameter calculating for *extreme* events in **October 2003**, according to actual data from high-latitude cosmic ray stations from the European database (http://www.nmdb.eu) by means of a robotic expert system: http://www.forshock.ru/pred.html Cyber-FORSHOCK. On the ordinate axis: the scale on the right (solid curve) - values of probability or fluctuation parameter; scale on the left (dashed curve) - the count speed in pulses for 5 minutes (averaged over 12 hours) by data of the neutron monitor of the Oulu station (Finland). The parameter values are enclosed in the interval: 0.35 <P <0.60 - the "Space noise" area. The abscissa is the date: year - month - day - hour.

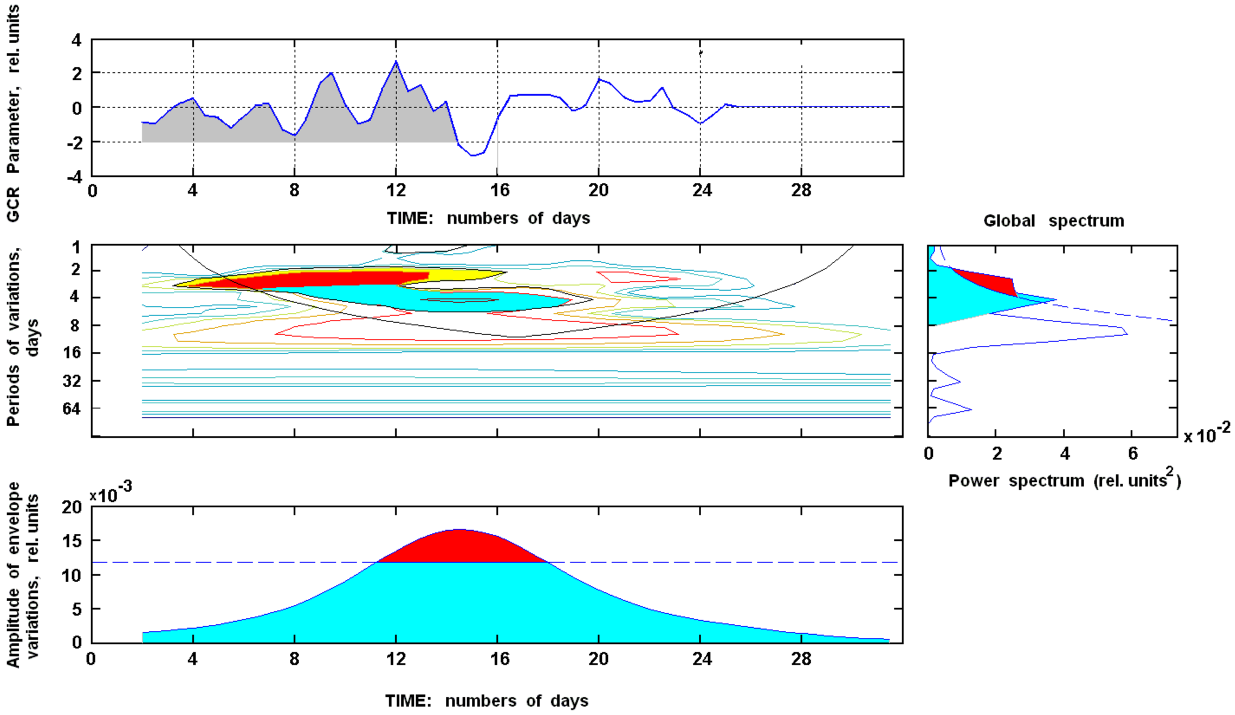


Fig. 4. Illustration of the process of nonlinear **steepening** of oscillations of the heliospheric current sheet in cosmic rays in **October-November 2003** based on the results of wavelet analysis. Oscillations in the period diagram are highlighted in color. In oscillations, a *trend* is clearly expressed in the high-frequency region: the systematic shift of the period of variations toward *smaller periods* (from **4** to **2** days). On the right - the global spectrum of oscillations for all analyzed period. Below is the envelope of the amplitudes of the oscillations in relative units.

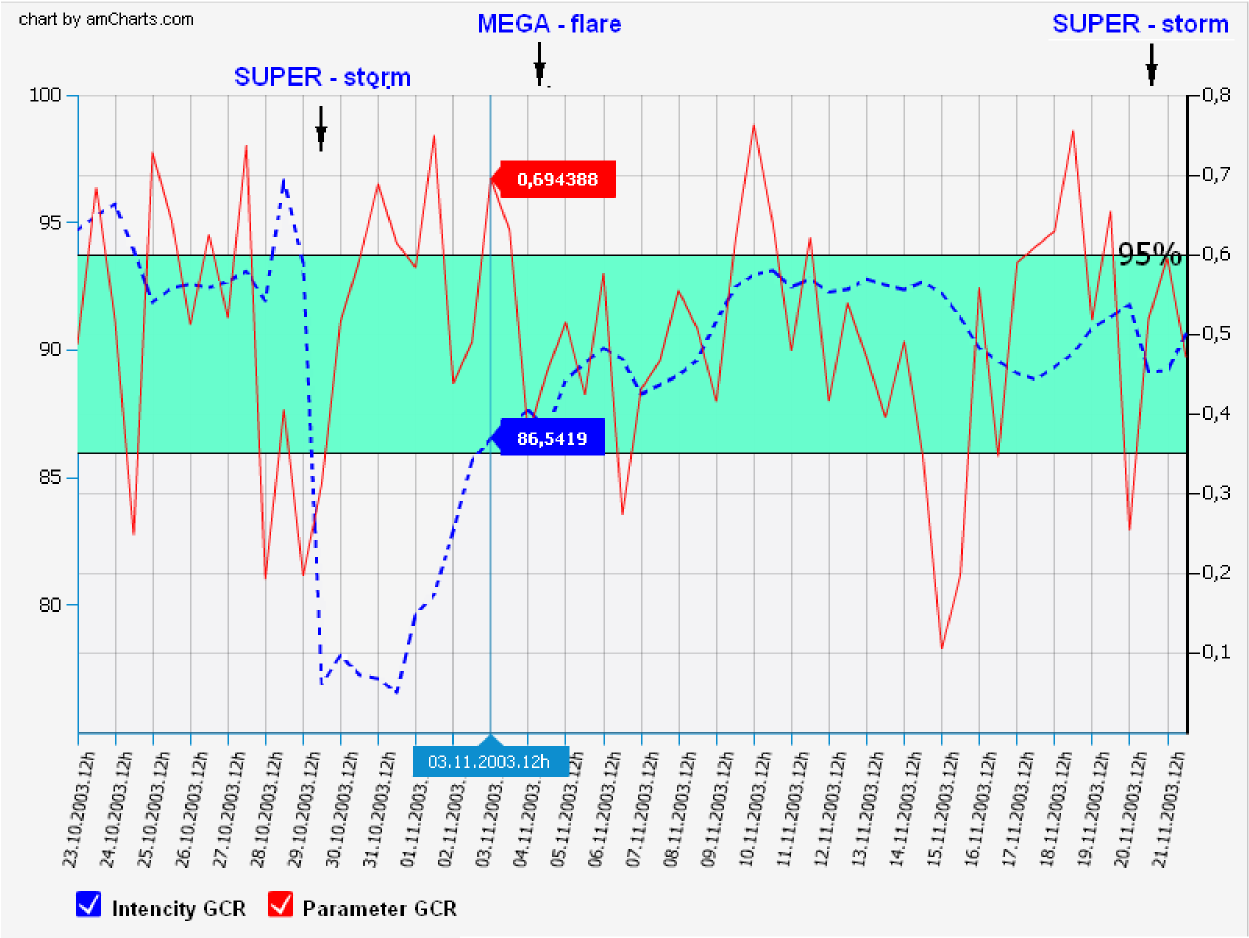


Fig. 5. Results of fluctuation parameter calculating on the example of extreme events in **October-November 2003**, according to actual data from high-latitude cosmic ray stations from the European database (http://www.nmdb.eu) by means of a robotic expert system: http://www.forshock.ru/pred.html Cyber-FORSHOCK. On the ordinate axis: the scale on the right (solid curve) - values of probability or fluctuation parameter; scale on the left (dashed curve) - the count speed in pulses for 5 minutes (averaged over 12 hours) by data of the neutron monitor of the Oulu station (Finland). The parameter values are enclosed in the interval: 0.35 <P <0.60 - the "Space noise" area. The abscissa is the date: year - month - day - hour.

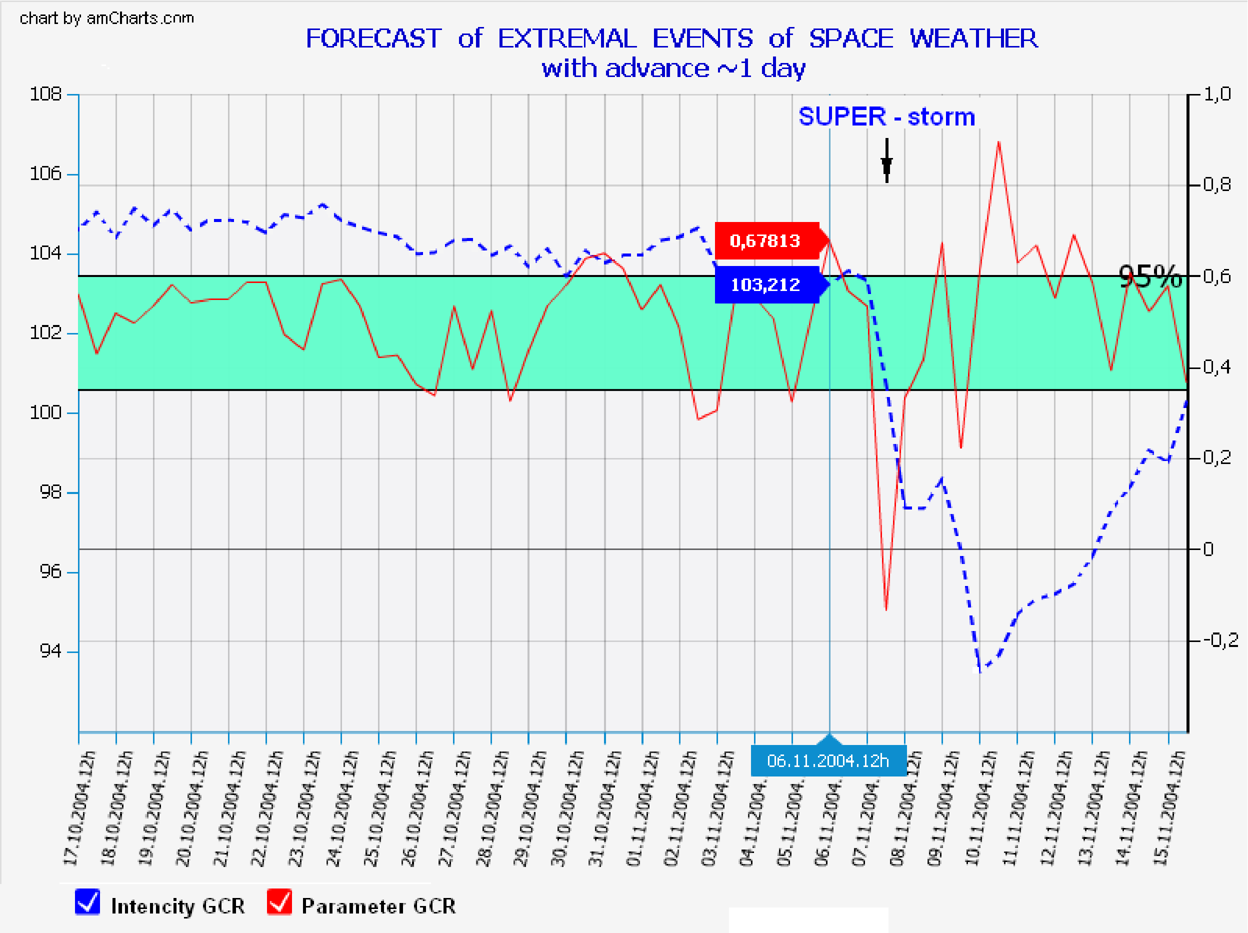


Fig. 6. Results of fluctuation parameter calculating in **October-November 2004**, according to actual data from high-latitude cosmic ray stations from the European database (http://www.nmdb.eu) by means of a robotic expert system: http://www.forshock.ru/pred.html Cyber-FORSHOCK. On the ordinate axis: the scale on the right (solid curve) - values of probability or fluctuation parameter; scale on the left (dashed curve) - the count speed in pulses for 5 minutes (averaged over 12 hours) by data of the neutron monitor of the Oulu station (Finland). The parameter values are enclosed in the interval: 0.35 <P <0.60 - the "Space noise" area. The abscissa is the date: year - month - day - hour.

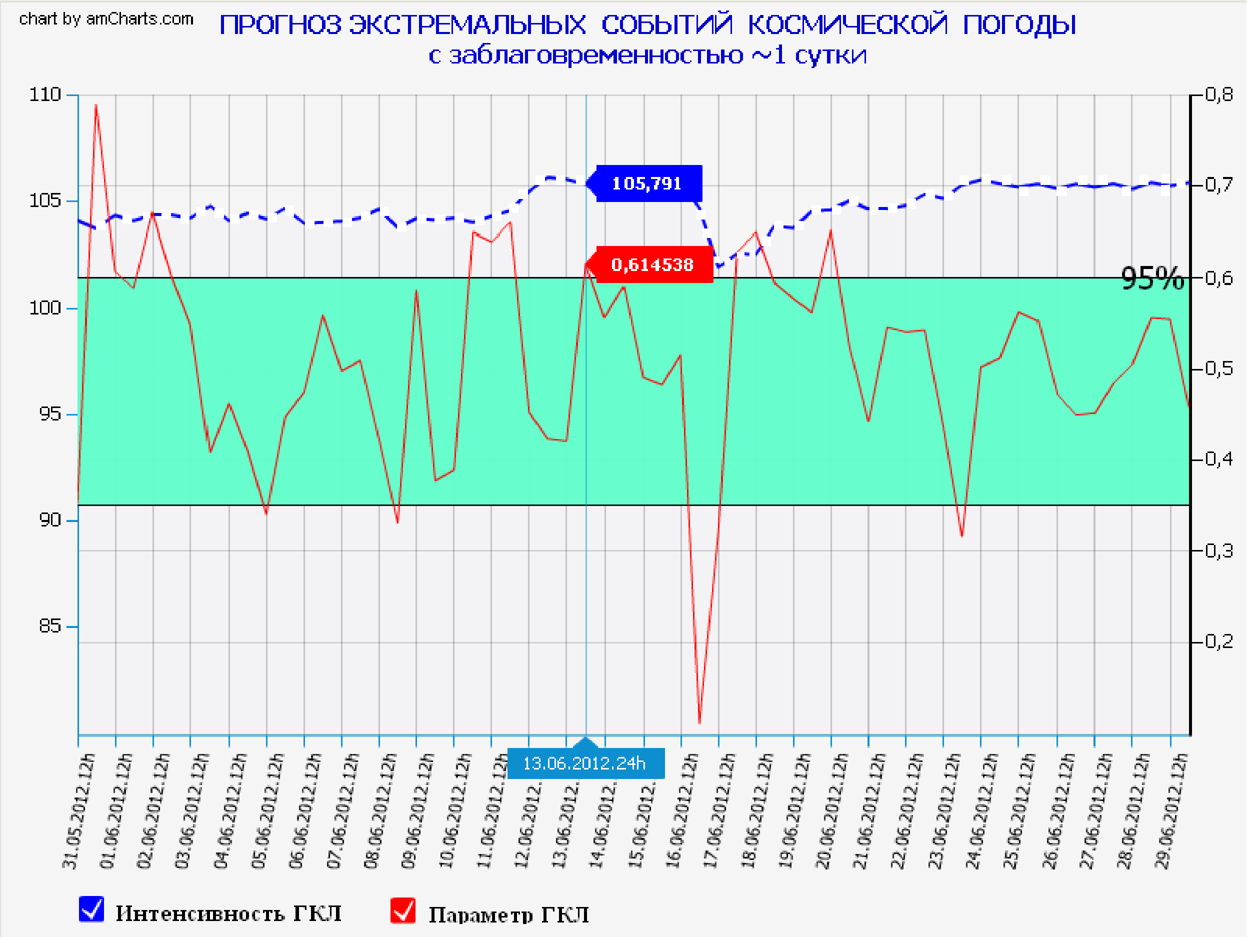


Fig. 7. Results of fluctuation parameter calculating in **May-June 2012**, according to actual data from high-latitude cosmic ray stations from the European database (http://www.nmdb.eu) by means of a robotic expert system: http://www.forshock.ru/pred.html Cyber-FORSHOCK. On the ordinate axis: the scale on the right (solid curve) - values of probability or fluctuation parameter; scale on the left (dashed curve) - the count speed in pulses for 5 minutes (averaged over 12 hours) by data of the neutron monitor of the Oulu station (Finland). The parameter values are enclosed in the interval: 0.35 <P <0.60 - the "Space noise" area. The abscissa is the date: year - month - day - hour.

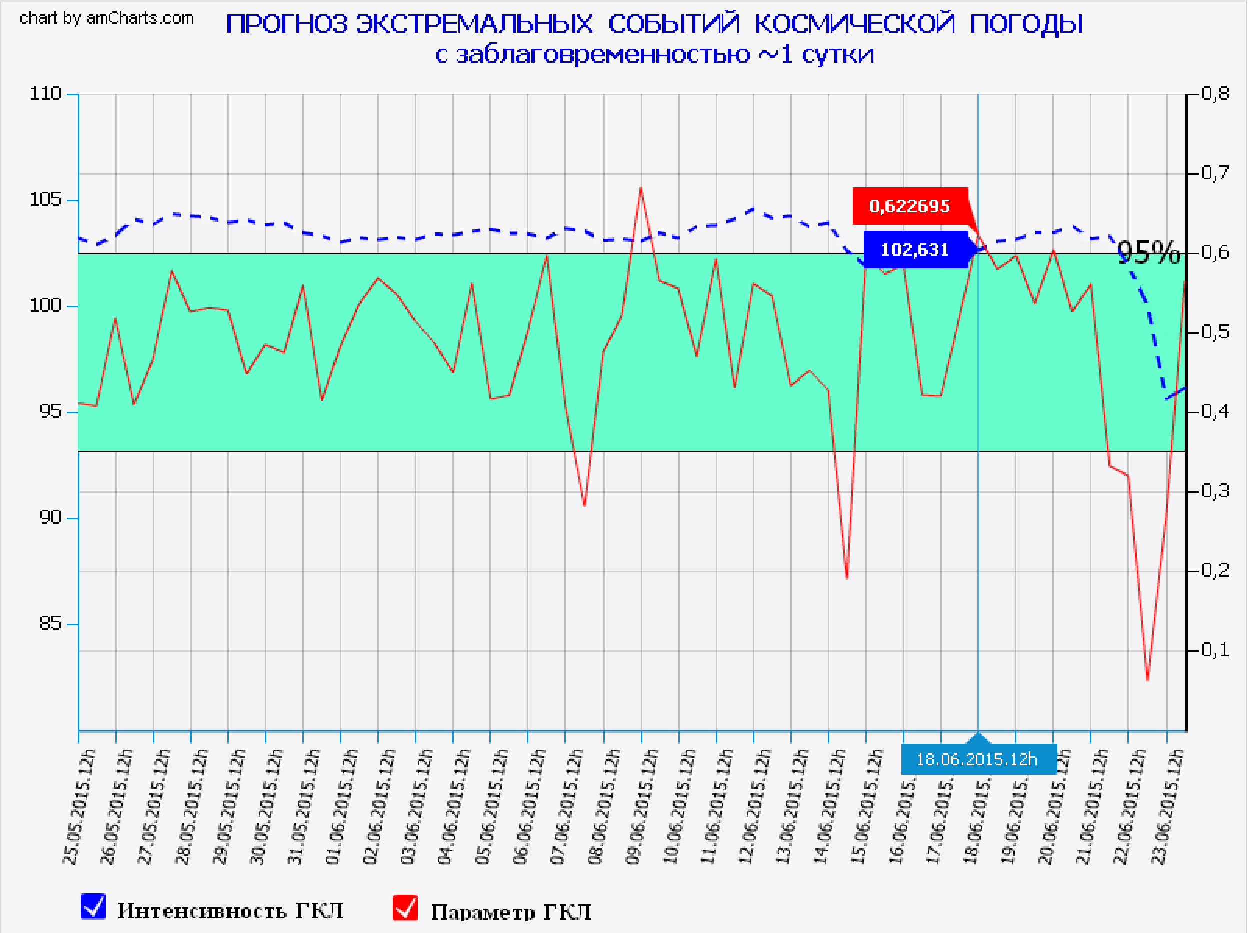


Fig. 8. Results of fluctuation parameter calculating in **May-June 2015**, according to actual data from high-latitude cosmic ray stations from the European database (http://www.nmdb.eu) by means of a robotic expert system: http://www.forshock.ru/pred.html Cyber-FORSHOCK. On the ordinate axis: the scale on the right (solid curve) - values of probability or fluctuation parameter; scale on the left (dashed curve) - the count speed in pulses for 5 minutes (averaged over 12 hours) by data of the neutron monitor of the Oulu station (Finland). The parameter values are enclosed in the interval: 0.35 <P <0.60 - the "Space noise" area. The abscissa is the date: year - month - day - hour.

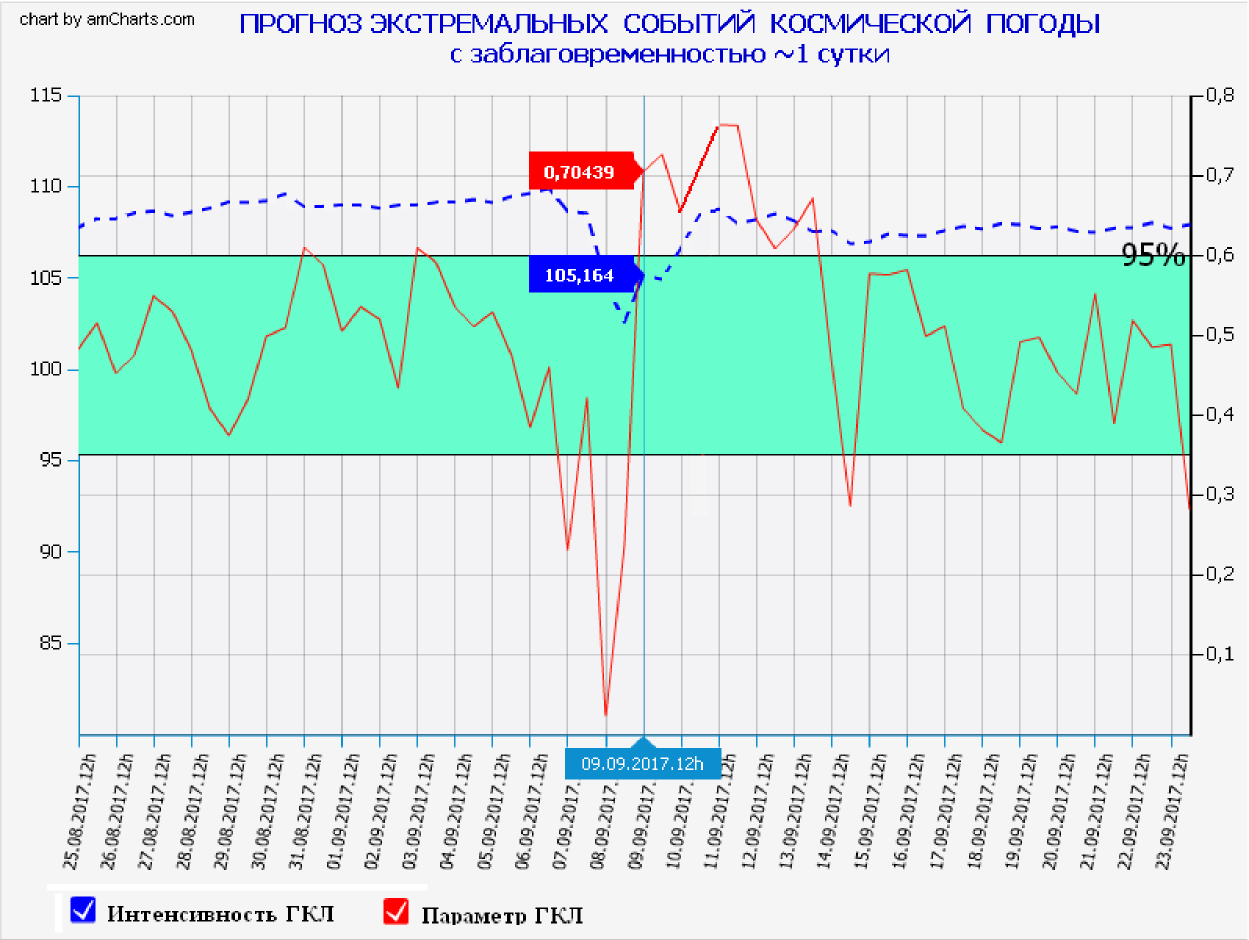


Fig. 9. Results of fluctuation parameter calculating in time of **September 2017**, according to actual data from high-latitude cosmic ray stations from the European database (http://www.nmdb.eu) by means of a robotic expert system: http://www.forshock.ru/pred.html Cyber-FORSHOCK. On the ordinate axis: the scale on the right (solid curve) - values of probability or fluctuation parameter; scale on the left (dashed curve) - the count speed in pulses for 5 minutes (averaged over 12 hours) by data of the neutron monitor of the Oulu station (Finland). The parameter values are enclosed in the interval: 0.35 <P <0.60 - the "Space noise" area. The abscissa is the date: year - month - day - hour.

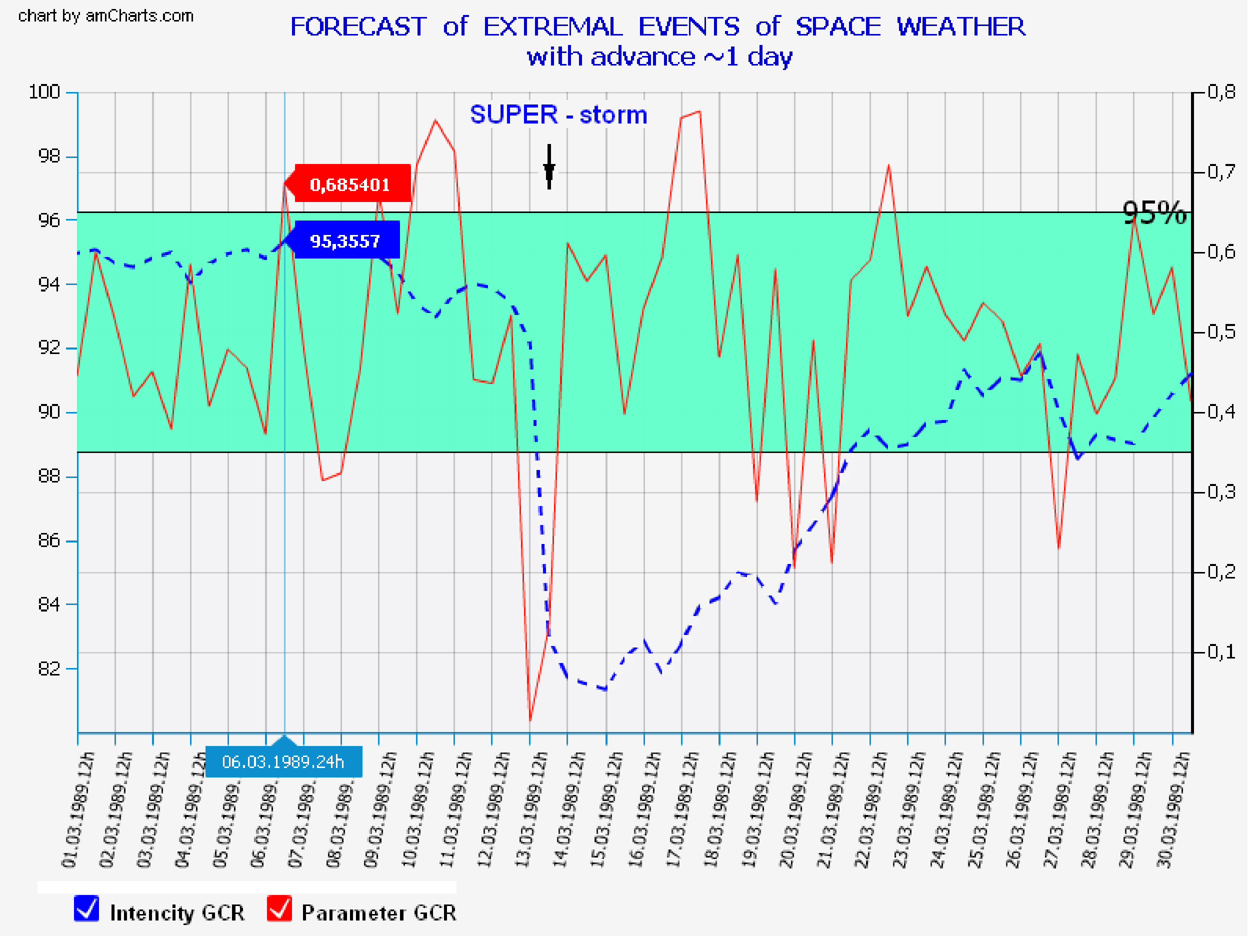


Fig. 10. Results of fluctuation parameter calculating in time of **SUPER-storm** in **March 1989**, according to actual data from high-latitude cosmic ray stations from the European database (http://www.nmdb.eu) by means of a robotic expert system: http://www.forshock.ru/pred.html Cyber-FORSHOCK. On the ordinate axis: the scale on the right (solid curve) - values of probability or fluctuation parameter; scale on the left (dashed curve) - the count speed in pulses for 5 minutes (averaged over 12 hours) by data of the neutron monitor of the Oulu station (Finland). The parameter values are enclosed in the interval: 0.35 <P <0.60 - the "Space noise" area. The abscissa is the date: year - month - day - hour.

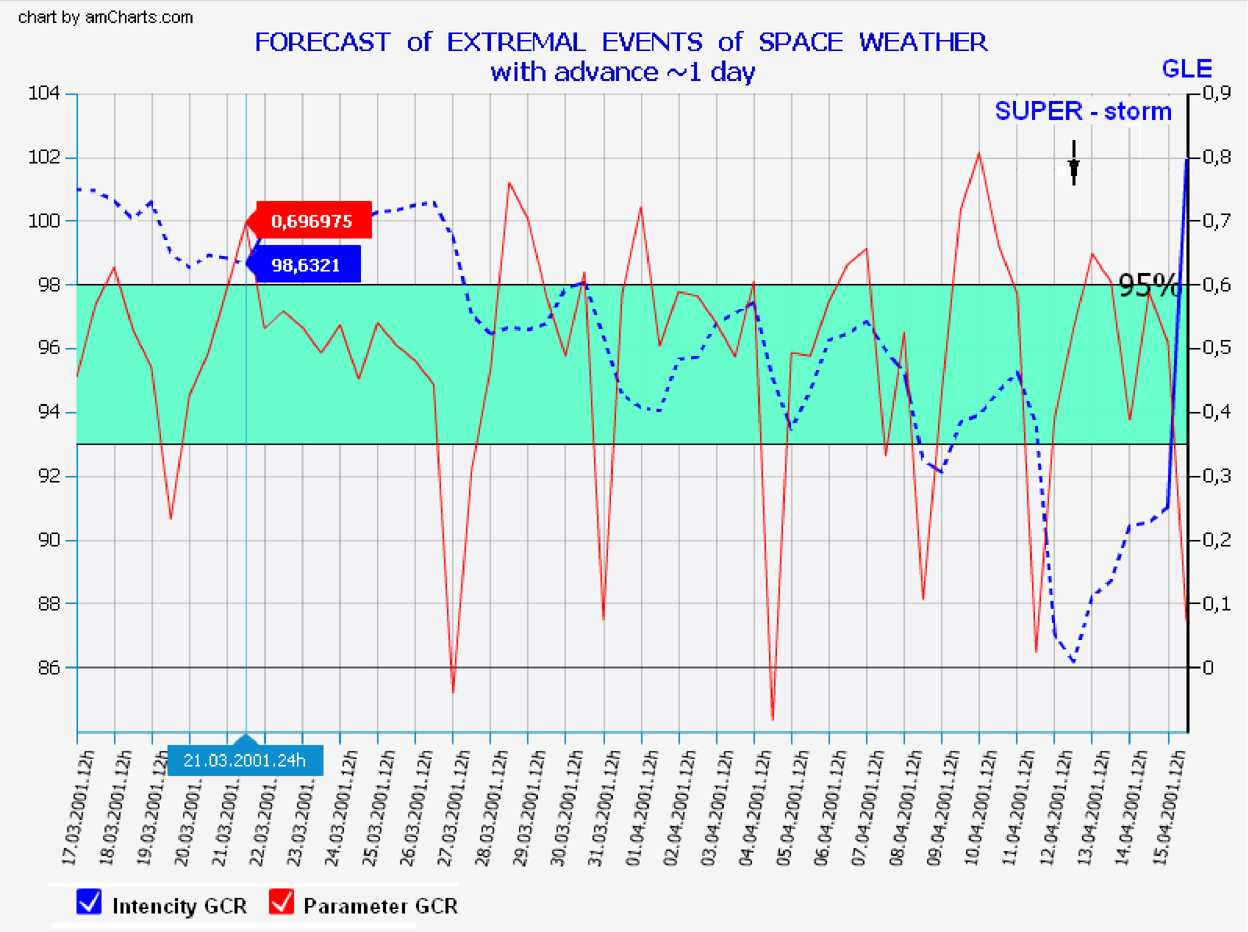


Fig. 11. Results of fluctuation parameter calculating in time of **SUPER-storm** in **11-12 April 2001**, according to actual data from high-latitude cosmic ray stations from the European database (http://www.nmdb.eu) by means of a robotic expert system: http://www.forshock.ru/pred.html Cyber-FORSHOCK. On the ordinate axis: the scale on the right (solid curve) - values of probability or fluctuation parameter; scale on the left (dashed curve) - the count speed in pulses for 5 minutes (averaged over 12 hours) by data of the neutron monitor of the Oulu station (Finland). The parameter values are enclosed in the interval: 0.35 <P <0.60 - the "Space noise" area. The abscissa is the date: year - month - day - hour.

Weibull distribution function:

$$F(x) = 1 - \exp\{-[(x-\theta)/b]^{c}\}$$

where

$\theta < x,\ b > 0,\ c > 0$

b - scale parameter

c - shape parameter

θ - pozition parameter

Distribution function density:

$$f(x) = c/b * [(x-\theta)/b]^{c-1} * \exp\hat{}\{-[(x-\theta)/b]^{c}\}$$

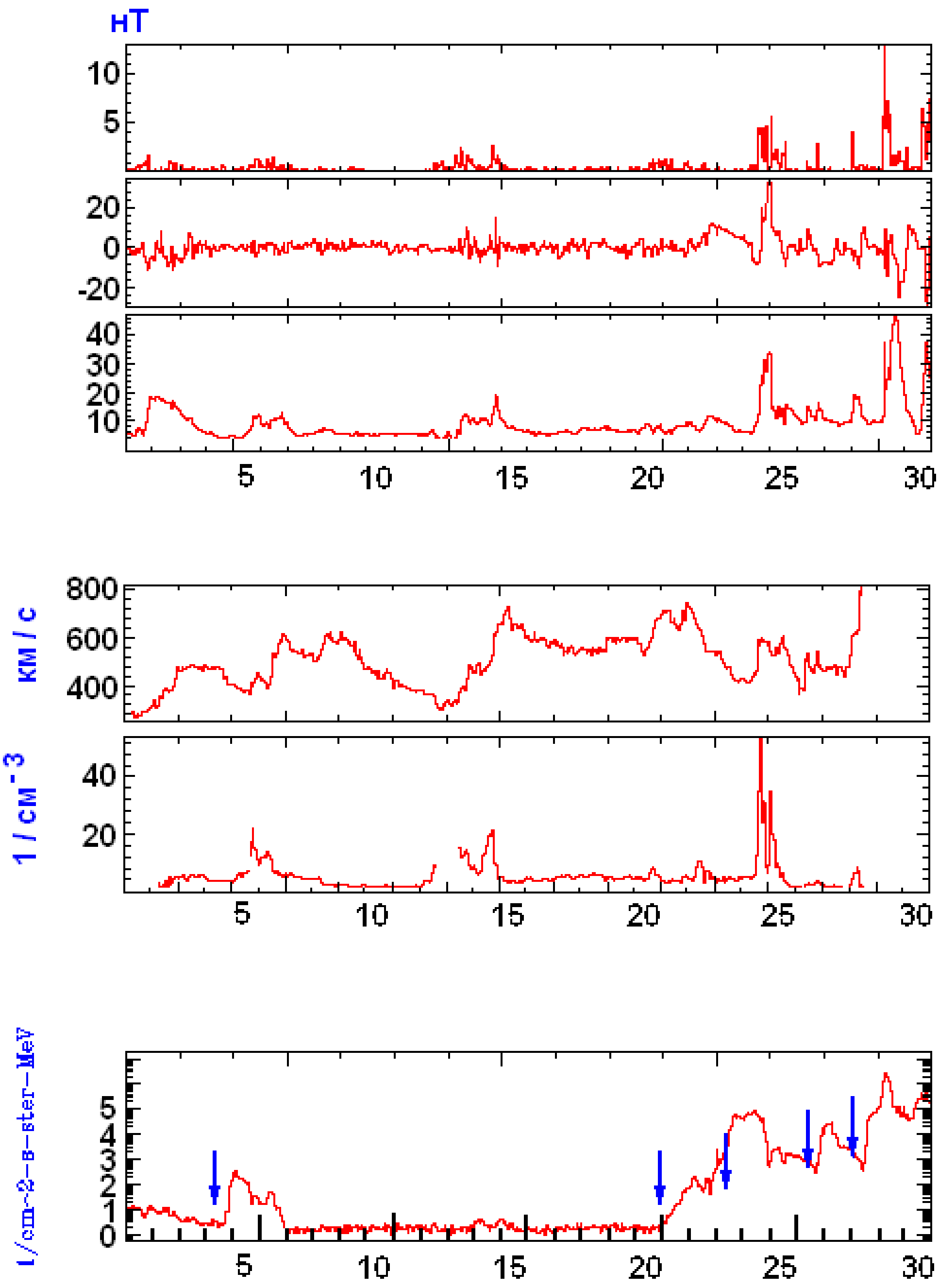
Reliability function:

$$R(x) = 1 - F(x)$$

Hazard function:

$$h(x)=f(x)/R(x)= [c*(x-\theta)^{(c-1)}] / b^{c}$$

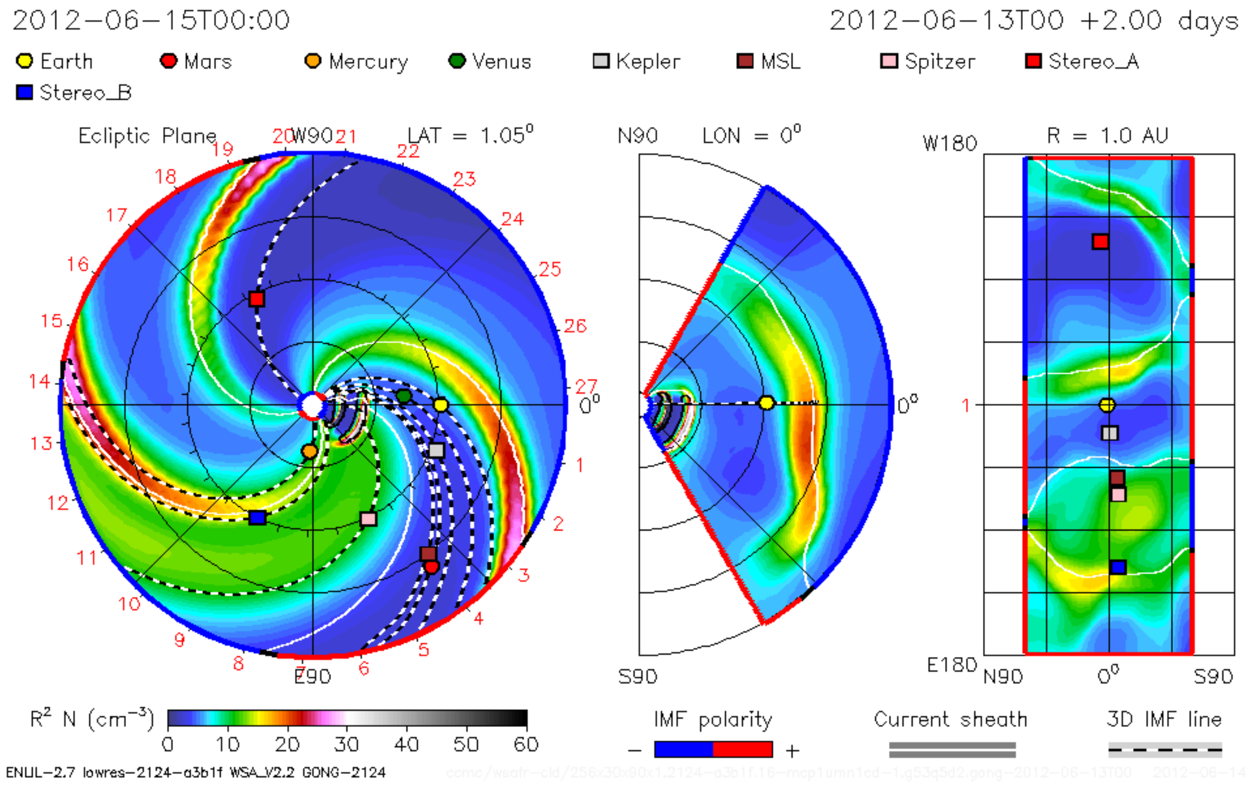
Appendix 1. Mathematical expressions determining the Risk function used in calculating the PARAMETER of cosmic ray fluctuations from the values of the shape parameter empirical histogram (c), scale (b) and shift (θ).



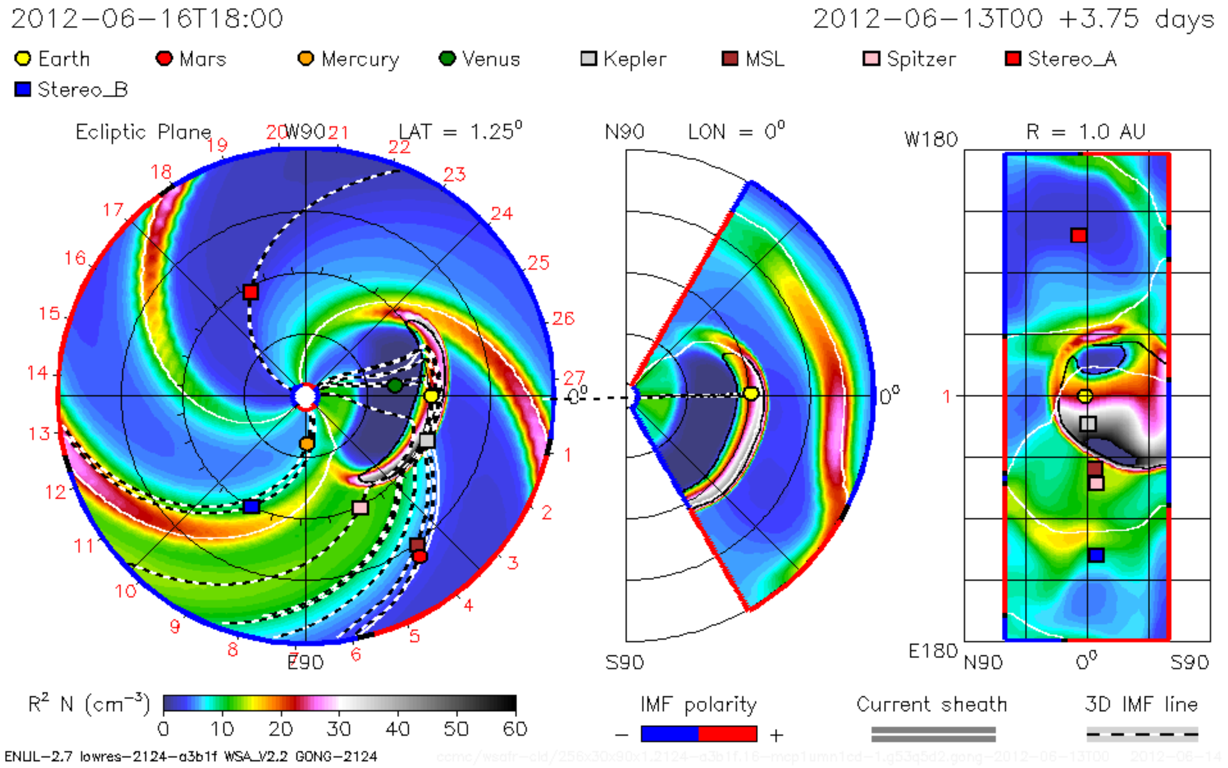
ВРЕМЯ: 01 - 30 октября 2003 г.

http://www.srl.caltech.edu/ACE/ASC/level2/

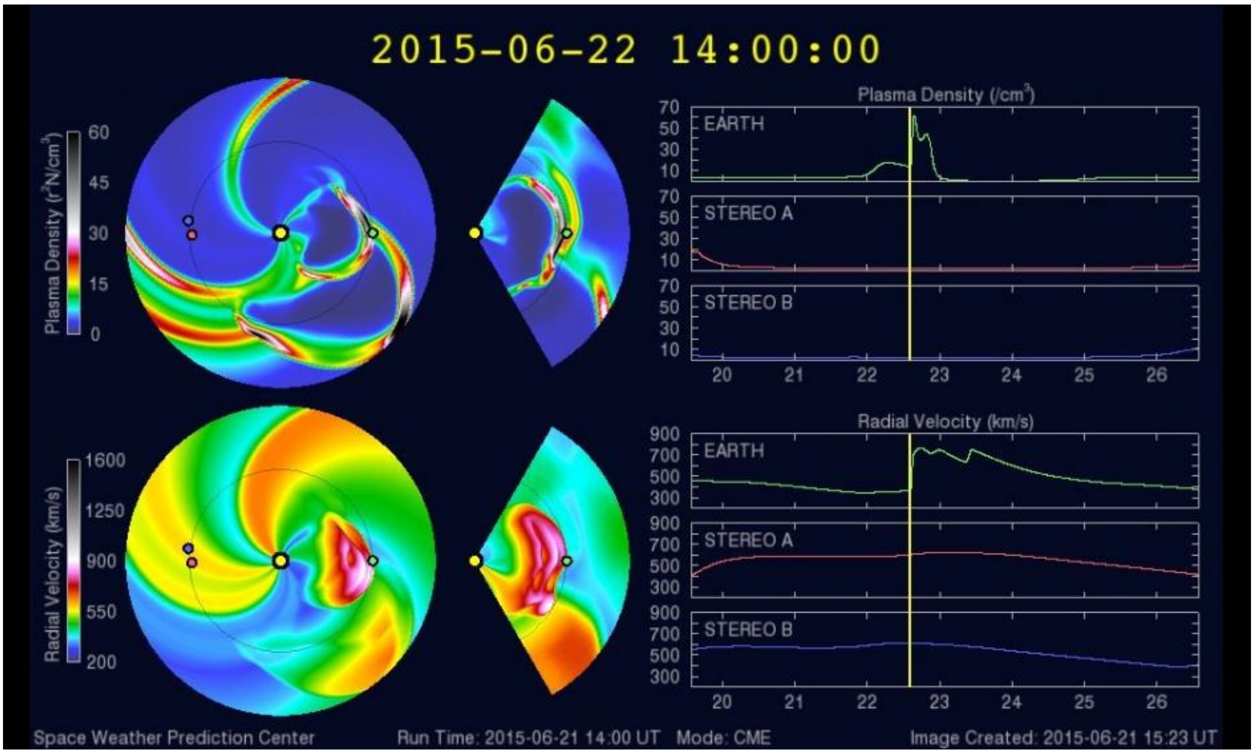
Appendix 2. The measurement data for the variance **σB** - a, **Bz**-component - b, and the module |**B**| of the interplanetary magnetic field - c, the velocity **V(r)** - d, and the density **ρ** – e, of the solar wind plasma from **October 1** to **October 30, 2003** on the ACE spacecraft. Streams of "storm" particles – f, low-energy protons (for example, particles with energy ~ 1 MeV) recorded in the third decade of October (October 21-30) 2003, according to direct measurements on the USA space vehicle **ACE**.



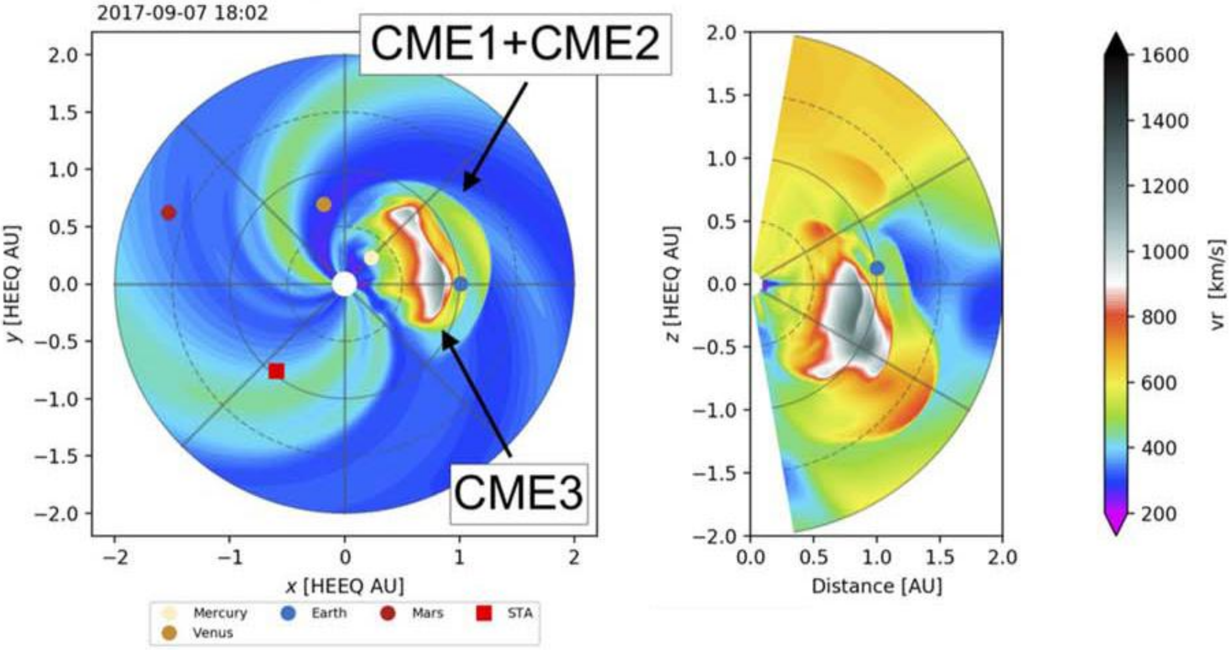
Appendix 3. Animation scheme for the dynamics of the extreme event on **June 15**, **2012** from the active region from the central meridian of the Sun, based on the model calculations of the Goddard Space Weather Lab from measurements on spacecraft Stereo-**A** and Stereo-**B**. Earth’s orbit is indicated by a **yellow circle** on the horizontal axis to the right of the disk of the Sun.



Appendix 4. Animation scheme for the dynamics of the extreme event on **June 16**, **2012** from the active region from the central meridian of the Sun, based on the model calculations of the Goddard Space Weather Lab from measurements on spacecraft Stereo-**A** and Stereo-**B**. Earth's orbit is indicated by a **yellow circle** on the horizontal axis to the right of the disk of the Sun.



Appendix 5. Animation scheme for the dynamics of the extreme event on **June 22**, **2015** from the active region from the central meridian of the Sun, based on the model calculations of the Goddard Space Weather Lab from measurements on spacecraft Stereo-**A** and Stereo-**B**. Earth's orbit is indicated by a **circle** on the horizontal axis to the right of the disk of the Sun.



Appendix 6. Results of simulation by system **EUHFORIA** of the interaction of the double **CME_1-2** from September 4-5, 2017 (from flares of class M4 and M5) with the third **CME-3** (from giant flare of class **X)** - September 6, 2017 [23].