COSMIC RAY VARIATIONS IN SOLAR ACTIVITY MINIMUM OF THE 24TH CYCLE

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The observed weakening of the global magnetic field of the Sun, which began at the end of the 22nd cycle of solar activity (SA) raises the question of the response of this phenomenon in cosmic rays (CR). Weak modulation in the 23rd and 24th cycles of SA is the result of the trend of the solar magnetic field in the last cycles. The work was carried out on the material of continuous CR observations by a network of neutron monitors, telescopes, and stratospheric balloon probes. The spectrum of CR variations in the minimum SA cycles was determined using the global spectrographic method developed by us. **The spectral characteristics of the variations of the anomalous 24th SA cycle are compared with the corresponding characteristics of the previous SA cycles (22-23) (base 1987). At an SA minimum of 24/25, a flat (confirming the drift modulation theory for qA=1) maximum of the CR flow is observed from 2017 to the present time. At the same time, the amplitude of variations for low-energy particles (observed in the stratosphere) exceeds the value of the base period variations by ~8%** and is 0.8% of the amplitude of the CR variations at the minimum of 23/24 in 2009. Max particle flow medium and high energies observed in neutron monitors and telescopes are 1-2% lower than that of 23/24.

The main attention in this work is paid to the determination of the spectral characteristics of CRs at the minima of cycles and to the features of CR modulation in cycles with different signs of the GMF of the Sun.

Data and method

The global spectrographic method (GSM) which was developed to determine the spectrum of long-term CR variations taking into account the rigidity dependence of variations based on all available information about CR intensity which was obtained during CR registration by a ground-based network of detectors and detectors probing the stratosphere. The analysis of the energy and temporal changes of the spectrum of CR variations was carried out for the period 1957-2020 when there were observational **data of neutron monitors (~ 40 stations of the world network), stratospheric balloon-probes (3 points) [4] and a telescope (Nagoya, [5]).** When using the GSM, the network of the listed detectors is considered as a single multidirectional detector equipped with high-precision standard instruments. **The characteristics of the rigidity spectrum which is given in the form $\delta(R) = a / (1 + bR^{\gamma})$ are obtained in zero harmonic approximation.**

Monthly mean CR variations were determined in % relative to the 1987 baseline.

We will consider and compare the CR modulation in three periods: 1991-1999 (qA> 0), 2000-2010 (qA <0) and 2014-2020 (qA> 0). To study the relationship between CR modulation and solar activity for each period and for different CR rigidities, the CR behavior will be modeled using multivariable regression.

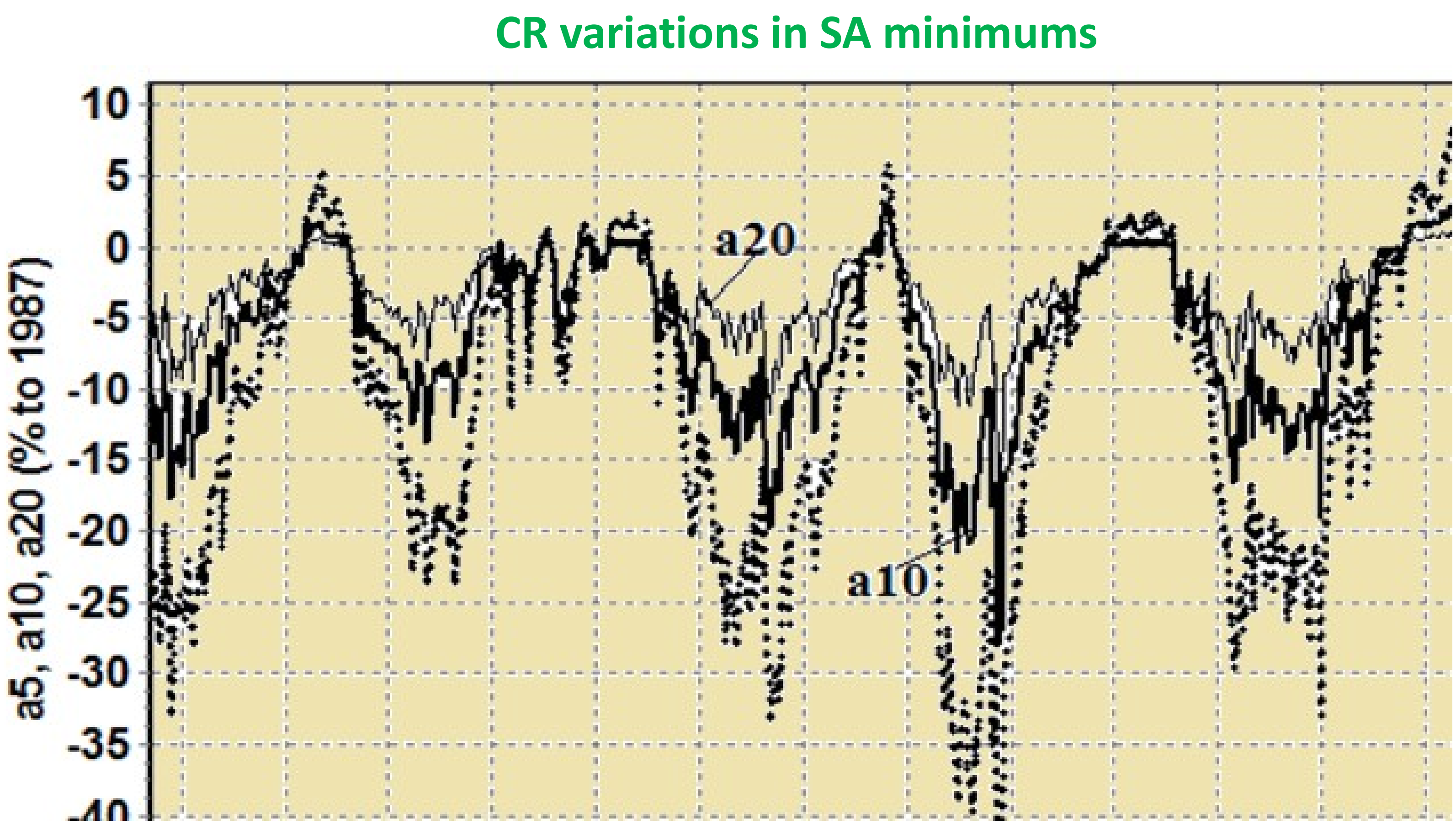

Figure 1. CR variations a5, a10, a20 (%. 1987), obtained on the basis of the complex of detectors: a5 (dashed line), a10 (bold), a20 (thin).

Figure 1 show the changes of the parameter *a* obtained by using the GSM and a three-parameter model of rigidity dependence of CR variations. The excess of the CR variations (both for particles with R=5 GV and for R=10, 20 GV) is observed in the minimum in 2009 in comparison with preceding minimums, and in the next minimum in 2019, variations for particles with R = 5, 10. 20 GV is slightly less.(Figure2. a-c)

Table 1. Amplitude of CR variations at minimums of 19-24 cycles for R=5, 10, 20 GV

	a,% to 1987					
R, GV	**1965**	**1977**	**1987**	**1997**	**2009**	**2019**
5	**3.4**	**1.1**	**0.0**	**1.5**	**8.6**	**6.8**
10	**1.1**	**0.2**	**0.1**	**0.3**	**3.3**	**2.1**
20	**0.4**	**0.0**	**0.1**	**0.1**	**1.1**	**0.7**

The values of the amplitudes in the last two minimums show an anomalously large increase of CR fluxes as a response of CR to the trend of magnetic field Sun.

The greatest increase is observed for low energies. In the last SA minimum (2019), the CR variations have a soft spectrum compared to previous minimums.

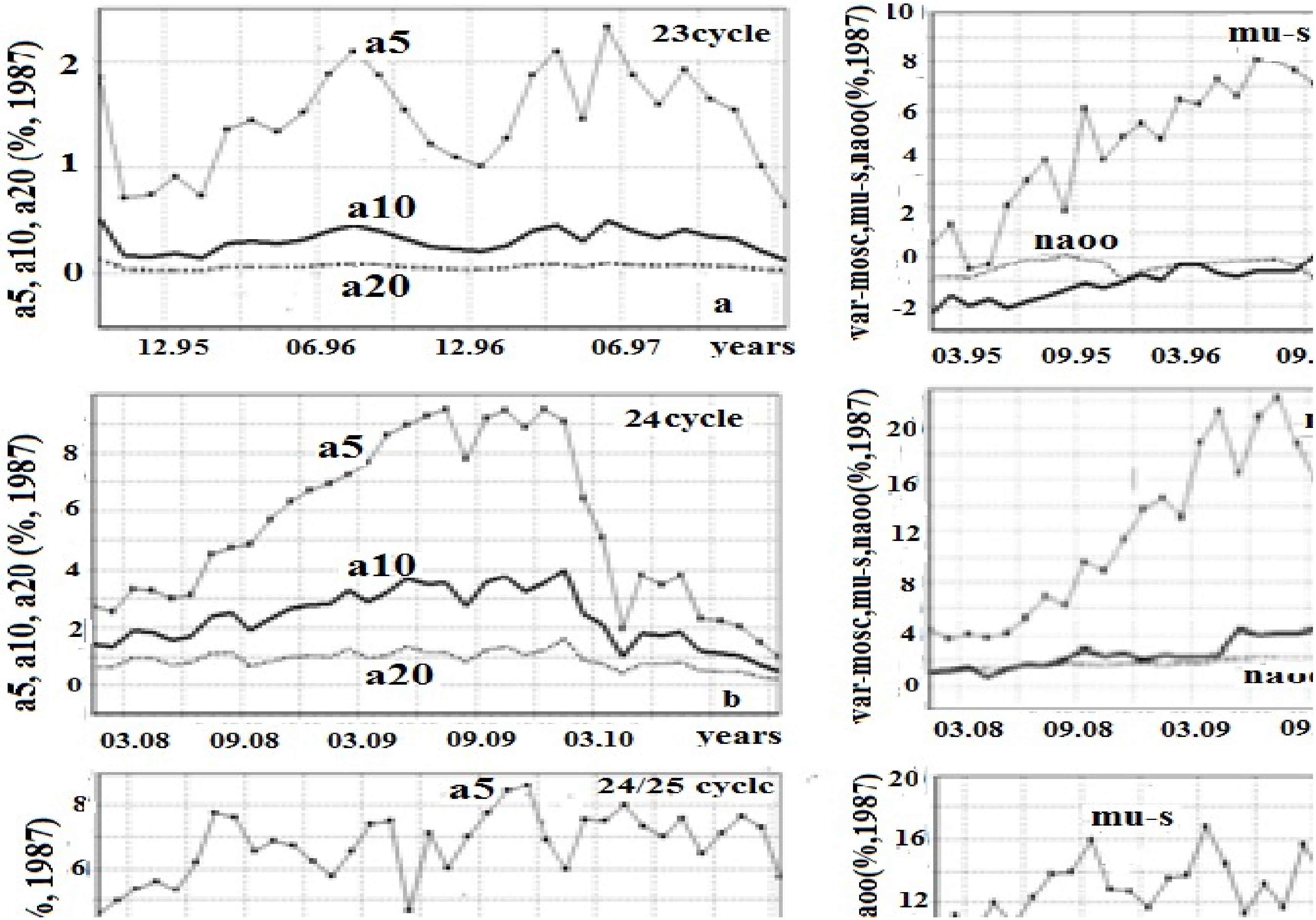

Figure 2. Amplitudes of CR variations in periods near SA minima in 23-24 cycles (a-c): a5-thin curves (with dots), a10-thick solid curves, a20-dashed curves; (a1-c1)-CR variations at the stations: mu-s (strat., Apatity), mosc (NM, Moscow), , naoo-telescope (Nagoya).

The analysis of obtained the amplitudes of CR variations a5, 10, 20, using a set of instruments and GSM carried out for periods of a relatively quiet heliosphere.
When studying CR modulation, the data of separate stations are often used as data on CR intensity. Therefore, CR modulation, the data of separate stations are often used as data on CR intensity.(Figure2. a1-c1)). In order to compare the characteristics of the density of restored CR fluxes for the same periods of SA minima, CR variations were determined for **individual stations** and observation points of CRs for different geomagnetic cutoff rigidity.

The analyzed CR variations in the periods close to the minimums of 20-24 SA cycles are divided by shape into two types of 11-year SA cycles: with a **sharp maximum** of the CR flux (**1965, 19/20), (1987, 21/22), (2009, 23 / 24)** and **flat maximums (1977, 20/21), (1997, 22/23), (2019, 24/25)** depending on the direction of GMF of the Sun.

As for the time of reaching **the maximum CR flux at the minimum in 1965 and in 1987, it reached by particles of different rigidity almost simultaneously** (for R = 5 GV in 05.1965 and R = 10-20 GV in 04.1965; for R = 5 - 10 GV in 03.1987 and R = 20GV in 02.1987), i.e. **with a slight advance, the maximum is reached by particles with high rigidity.**

the time variation of flat CR variations in SA minima in cycles with the direction of the solar polar field **qA> 0**, the first thing to note is **some ambiguity in determining the CR maximum. the maxima of the reconstructed fluxes for different rigidities in cycles 21 and 23 do not exceed 2% and their values are close in different months.**

For a minimum of 24/25, the variations of low-energy particles differ significantly from variations in other cycles with the same direction of the GMF: the a5 amplitude reaches 8.5% at the end of 2019. The height of the restored CR fluxes is 24/25 for **medium- and high-energy** particles **exceeds** the modulation in cycles with a similar direction of the magnetic field, **but insignificantly** (a10 = 3.1%, a20 = 1.1% in 10.2019).

This circumstance may indicate a softening of the spectrum at a minimum of 24/25; confirmation of this is the result of determining spectrum index γ (Figure 3),

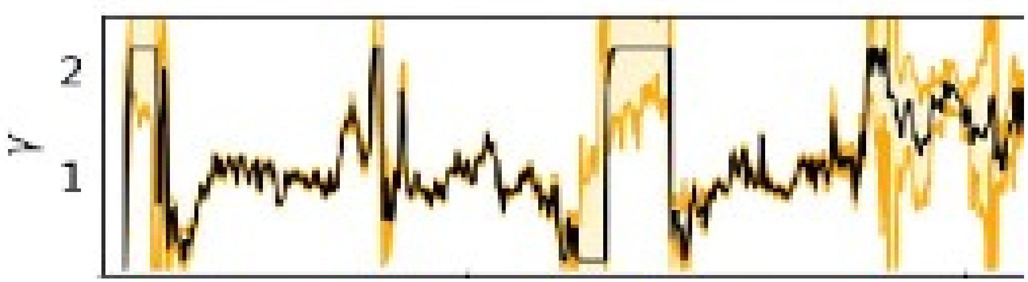

Figure 3.Temporal changes of spectrum index γ

Comparison of the *γ* spectrum index for the minimums of the three cycles(22/23, 23/24 and 24/25) shows that the softening began in 24/25 already from 2017 (γ = 2), for 23/24 - γ = 1.8, for 22/23- γ = 0.9.

The soft spectrum of long-term CR variations obtained by us in a minimum of 24/25 is confirmed by the results [Shuai Fu, X. Zhang, L. Zhao, et al.,2021], obtained with the use of ACE CRIS and NM data.

Variations calculated using a set of instruments for R=5, 10, 20 GV does not contradict the variations obtained for individual detectors (Figure 2. a1-c1) in general, but data the separate monitor sometimes does not allow making a correct conclusion about modulation. If, when obtaining the variations for R=5, 10, 20 GV, the accuracy is determined by the adequacy of the CR variation model used, then for many operating stations CRs the accuracy is characterized by sporadic changes in efficiency and drift of the data CR registration. The issue of long-term stability of detectors is described in detail in [Belov A.V., et. al., 2007], the conclusions of which **indicate the advantages of using the model approach to determine the spectral characteristics.**

Long-term variations in CR and solar - heliospheric indices

The relationship between the observed CR flux and solar-hediospheric cyclic activity is confirmed by the results of long-term observations of the Sun, heliospheric characteristics, and CRs on earth and in space.

The result of the recently observed trend of the main parameter modulating CR - the global magnetic field of the Sun, its significant and long-continued weakening, ultimately leads to a trend in the characteristics of the SA and the heliospheric field, namely: the polar magnetic field of the Sun (Hpol), the energy characteristic large-scale solar field (Bss), induction imf (Bimf), area of low-latitude coronal holes (Al), sporadic solar activity (CME index), and inclination of the neutral layer (η). **The effect on the observed CR modulation of solar – heliospheric characteristics occurs through the chain. Figure 4 shows the long-term changes in the participants in an interconnected chain.**

Long-term variations in CR and solar - heliospheric indices in 21-24 cycles

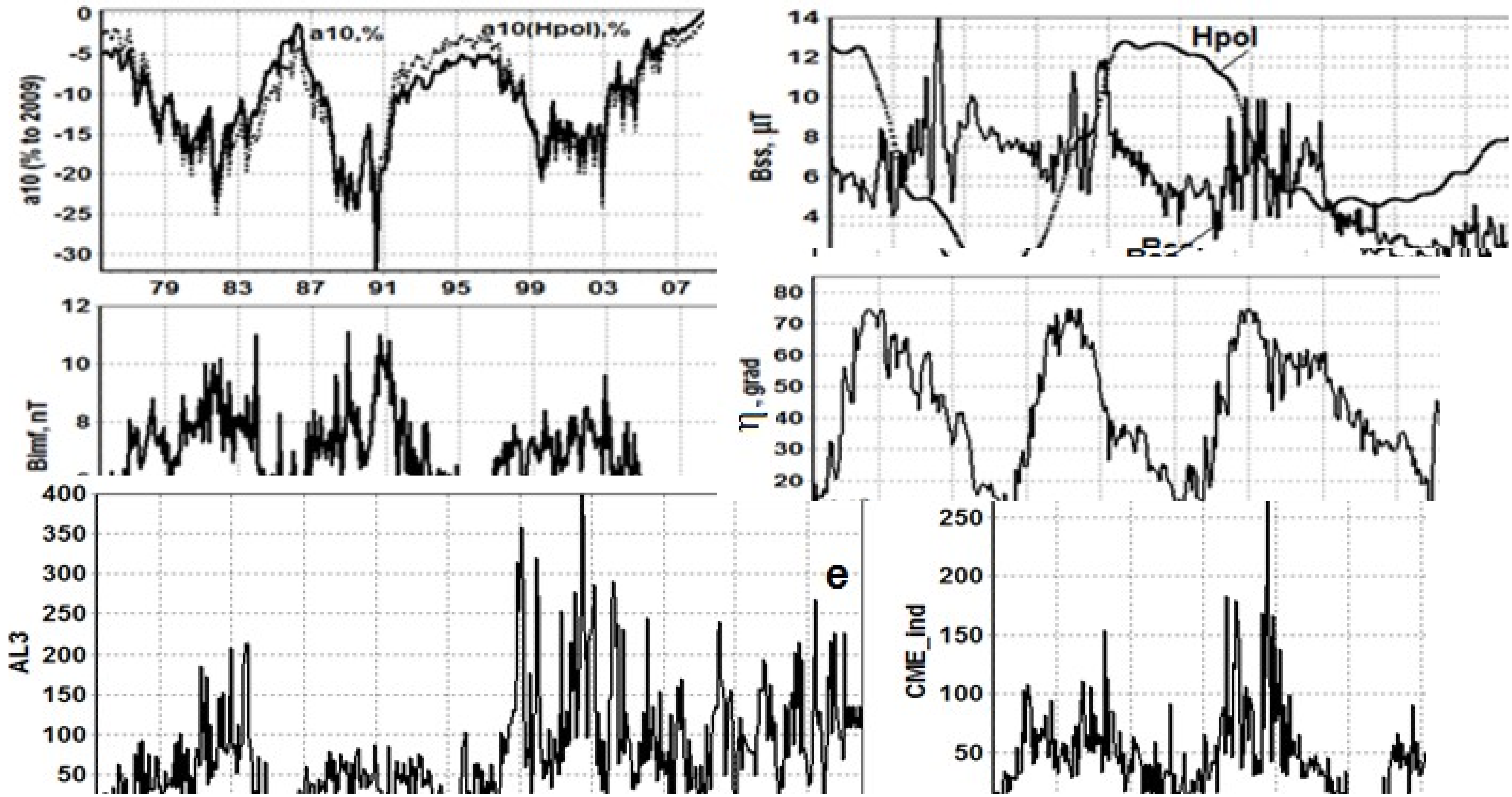

Figure 4. Behavior of: a) variations in the CR density with a rigidity of 10 GV (a10,% - solid curve: - A10 $_{Hpol}$,% variations with the introduced correction for the influence of Hpol - dashed line,); b) - mean magnetic field of the Sun (Bss); polar field of the Sun (Hpol); c) - magnetic induction of the interplanetary magnetic field near the Earth (Bimf); d) - the slope of the heliospheric current sheet (η); e)-area of low-latitude coronal holes; f) -CME index.

To simulate CR modulation by electromagnetic fields of the heliosphere, we have proposed a semiempirical multiparameter model [3, 8], in which the long-term modulation of CR is described by the above-mentioned characteristics η, B_{ss}, H_{pol}, CME*i* and *Al*

For these indices and amplitudes of the isotropic part of CR variations with rigidity 5, 10, 20 GV (*a5, a10, a20*,% to 1987), a multivariable regression analysis was performed taking into account the delay for each modulation parameter and the role of each of them in CR modulation was revealed in 1991-1999, 2000-2013 and 2014-2020.

as a modulation characteristic of heliospheric field in the model instead of IMF (B_{imf}), the field on the surface of the solar wind source B_{ss} is used. It was shown in the work [Belov A.V., et. al., 2007] that replacing module B_{imf} by the mean magnetic field on the surface of the solar wind source B_{ss} in the empirical model is not only possible but even improves the quality of the model.

The modulation in the minimum of the 24/25 cycle is compared with the modulation of the previous cycles 22/23 and 23/24, in order to compare the dependence of the modulation of particles of different rigidity from the direction of the GMF.

As a result of the model description of CR variations, which was carried out separately for the amplitudes a5, a10, and a20 for three periods, the following values were obtained:1) the correlation coefficient ρ =0.96-0.98, the standard deviation of the model σ ~0.34% - 2.43%.

We consider the possible reasons for CR modulation with quantitative estimates of the contribution of various characteristics of SA to the observed CR modulation in the period 2014-2020. (qA> 0) and **comparison** with contributions in **1991-1999 (qA> 0) and 2000-2013 (q <0) was carried out.**

Contributions to CR modulation from changes in SA characteristics

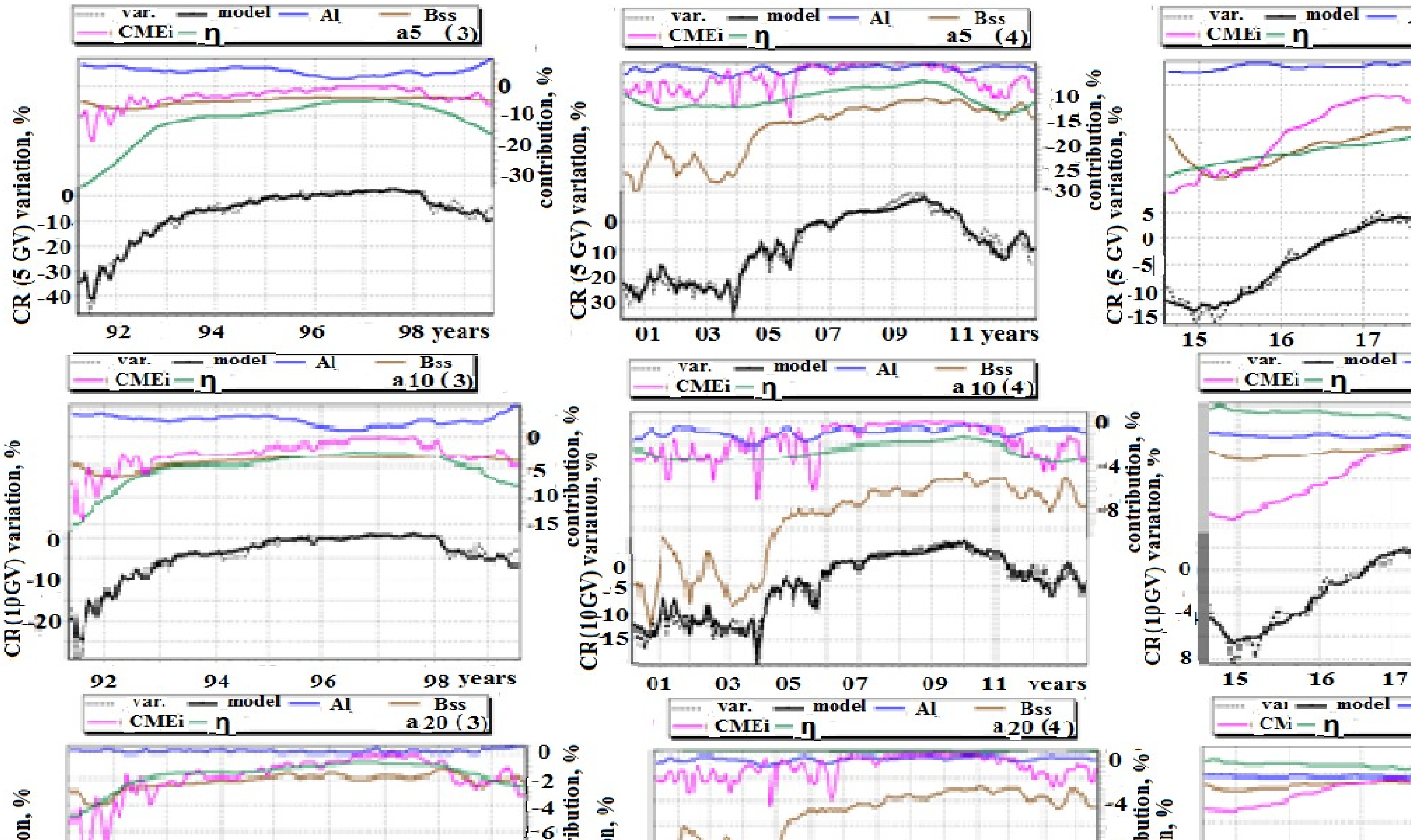

Figure 5: A- a5, B- a10, C- a20 (%,1987) – CR variations (dashed line in the lower part) and the result of their modeling (solid black); upper part-contribution from: *η* (green), *Bss* (brown), CME*i* (pink) and *Al* (blue): (3) - 1991-1999, (4) 2000-2013 and (5) -2014-2020.

Analyzing the obtained model results : 1. In the period **1991-1997 qA> 0 for R = 5 GV**, the **decisive role at creating of modulation in terms of the contribution (11.7%) belongs to the current sheet slope *η*. 2.** For **R = 10 GV and R = 20 GV** for the period 1991-1997, the contributions to modulation from **the action of *η* and *Bss* differ insignificantly.**

3. for the period 2000-2013 q <0, CR modulation is mainly determined by changing of B_{ss} characteristic for the entire rigidity interval

4. For the period 2014-2020 qA> 0, the main role in creating CR **modulation for R = 5 GV** is played by the **mean magnetic field B_{ss} (6.4,%) and the current sheet slope *η* (5.3,%)** with ~ the same contribution.

For particles with rigidity 10 and 20 GV, with general small amplitude of variations in this period, the contribution from the influence of the CMEi on modulation is slightly higher (an increase of the CMEi at the end of 2014).
About the interaction of the main modulation mechanisms and the role of modulation characteristics in creating general modulation changes with solar cycles is stated in [Belov A.V., Gushchina R.T., Yanke V.G. 2017; Potgieter, M., 2013].

Comparing the modulation of particles of different energies during periods with the same direction of the GMF, we note that at the SA minimum, the *η* values fall, which can be reflected in the drift effect during propagation CR. In the presented modulation model, the contribution to the overall modulation from the effect of CR drift in the 24th cycle is lower.
significantly smaller value of the drift effect in the incipient minimum (2017-2018) 24/25, obtain in [Modzelewska R., et. al., *2019*]

In the modulation model for the period **2000-2013 qA <0**, the predominance of the contribution from the impact on CRs of **a large-scale magnetic field on the Sun, expressed in the value of the B_{ss} index**, may indicate an **increase in the role of CR diffusion during propagation in the heliosphere with reduced IMF** [Kalinin et. al. *2017*]. The predominance of the diffusion process in CR modulation at qA <0 (in our analysis, the period 2000-2013) is also confirmed by the results of [Modzelewska R., et. al*., 2019*].

Conclusion

1.The amplitudes of long-term CR variations in the minimums and near the SA minimums give an idea about the complex nature of modulation of particles of different energies in periods with different directions of the solar GMF. The recovered particle fluxes during periods of low SA differ in height and time to reach a maximum for the analyzed rigidities of 5, 10, 20 GV. **For a minimum of 24/25, the variations of low-energy particles differ significantly from variations in other cycles with the same direction of the solar polar field qA> 0, the value of a5 reaches 8.5% (in cycles 21 and 23, it does not exceed 2%). The height of the reconstructed CR fluxes of 24/25 for medium- and high-energy particles exceed the modulation in cycles with a similar magnetic field direction, but insignificantly (a10 = 3.1%, a20 = 1.1%). This circumstance indicates a softening of the spectrum** at a minimum of 24/25; which **is confirmed by the result of determining the index** γ. Mitigation began on 24/25 from 2017 (γ = 2), for 23/24 - γ = 1.8, for 22/23 - γ =0.9.

2.The **restored CR flux at the 24/25 minimum is lower than in the anomalous 23/24, and the dependence of recovery level from the particle energy is observed. For the period 2014-2020 qA> 0, the main role of creating CR modulation for R = 5 GV is played by the mean magnetic field B_{ss} and the current sheet slope η with ~ the same contribution.** For particles with R=10 and 20 GV, with a general small amplitude of variations in this period, the contribution from the influence on the modulation of the CMEi index slightly exceeds the corresponding contribution in other periods.

3. **At a minimum of 24/25, a decrease of the influence η on the CR modulation was revealed**. The change in its value occurs within the same limits as in other cycles, but the effectiveness of the effect on modulation is greatly reduced. **In the 24th and the beginning of the 25th SA cycle, the impact on CR of a large-scale magnetic field on the Sun, expressed in the B_{ss} index, prevails in the general CR modulation, despite a decrease in the B_{ss} value itself.**

4. The conducted study says about the **advantages of using the GSM and the model approach in the study of long-term variations, rather than the CR registration data at individual stations.**

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