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Index of the Long-Term Influence of Sporadic Solar Activity on Cosmic Ray Modulation

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Abstract—Coronal mass ejections (CMEs) not only produce Forbush effects but contribute to long-term modulations of cosmic rays. That makes coronal ejections the main sporadic manifestations of the solar activity, which should be considered in modulation models. In this paper, a new version of the CME-index is proposed based on a comparison of the data from satellite coronographs with Forbush effects and long-term variations of cosmic rays.

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1. INTRODUCTION

The sporadic solar phenomena, primarily coronal mass ejections (CME), influence galactic cosmic rays (CRs). When an ejection arrives at the Earth, a Forbush decrease is observed in CRs (for example, (Forbush, 1954; Lockwood, 1971; Cane, 2000; Belov, 2009)) and this effect can be quite significant. According to the data obtained from ground neutron monitors, the greatest Forbush decreases reach ~30%, exceeding by amplitude CR variations determined by quasi-11-year cycles of solar activity (Belov, 2009).

The main effect is normally observed in CRs within a few days after the events on the Sun, but the interplanetary disturbance caused by CMEs can stay in the heliosphere for a few months, persistently affecting CR. Suppositions brought forward some time ago (Lockwood, 1971) that Forbush decreases make the main contribution to the considered CR long-term variations are wrong, since long-term CR variations are mainly produced by cyclic changes of solar magnetic field strength and configuration, which, among other effects, cause modifications in the shape of the heliospheric current sheet (Krymsky et al., 2001; Belov et al., 2002). However, the contribution of sporadic phenomena is considerable and should not be neglected (Cliver et al., 2013).

The long-term variation model that our team has been developing (Belov et al., 2002) is based on several indices calculated for the surface of a source of solar wind (Hoeksema and Scherrer, 1986). The considered indices, including the inclination of the heliospheric current sheet and the mean and polar magnetic fields of the Sun, are slowly varying parameters that determine the structure and the state of the heliomagnetosphere. We recently complemented the list with an area of low-latitude coronal holes (Gushchina et al., 2016), which is also an index with cyclical behavior. These indices, in the aggregate, reproduce the observed long-term variations of a CR with a rigidity of 10 GV. At the same time, they do not consider sporadic phenomena and a considerable part of short-term variations. We needed an additional index to consider the effect of sporadic phenomena, primarily Forbush effects (FEs). From the very beginning, we understood that information on CMEs would be the best index in this regard. Anyway, this information was not available until recently, so we tried to replace it with other data. Trial calculations showed that the known solar flare index (Atac, 1987) poorly describes short-term variations and actually doubles the number of sunspots. The X-ray solar flare index *xf* (Belov et al., 2007) proved to be much more useful, but it solves the problem only partially. First, most flares, including the strong ones, are in no way associated with the observed CR variations; second, ample and homogeneous X-ray observations of the Sun have been carried out from 1975, while the homogeneous series of CR variations that we have been studying dates back to 1953. To explore the whole period of cycles 19–24, we used the number of geomagnetic storm sudden commencements N_{SSC} as sporadic phenomenon index I_{SC}.

This index is more closely connected with FE, but it still has apparent deficiencies. We aimed to develop a completely solar model, while the I_{SC} index obviously lacks globality. The same refers to any other index based on geophysical data or observations of solar wind in the near-Earth medium.

Thus far, the period of observation of Soho/LASCO coronographs has exceeded 20 years, and every subsequent year increases the appeal of the use of CME direct observation to study CR long-term variations. A monthly CME-index was proposed and calculated by Mavromichalaki and Paouris (2012). Its inclusion in the model of long-term CR modulation for cycles 23–24 shows good results (Paouris et al., 2012, Paouris et al., 2015; Gushchina et al., 2014), and the model agreement with experimental data has noticeably improved. At the same time, it is clear that the CME-index can be significantly upgraded.

In this paper, we propose a new version of the CME-index obtained from comparison of the data from satellite coronographs with FE and long-term CR modulation.

2. THE DATA

We obtained long-term CR variations for 1957–2015, applying the technique presented by Belov et al. (1993) and using monthly mean data from ground neutron monitors and stratosphere observations (Stozhkov et al., 2007). Additionally, FE characteristics obtained by the global survey method based on hourly mean data of the global net of neutron monitors accumulated in the database on FE and interplanetary disturbances (Belov, 2009) are used in this paper. All CR variations are given for a rigidity of 10 GV.

The CME-index was found from observations of Soho/LASCO coronographs assembled in a convenient and useful database (Yashiro et al., 2004, http://cdaw.gsfc.nasa.gov/CME_list/). Information on geomagnetic storm sudden commencement (N_{SSC}) was obtained from the website [http://www.wdcb.ru/stp/data/sudden.com/ssc.dat].

3. CME-INDEX

Any solar plasma cloud travelling into the interplanetary space carries its magnetic field and influences CRs. Any ICME (CME continuation in the solar wind) is associated with FEs, (Lockwood, 1971; Cane, 2000; Belov, 2009) which are frequently (but not necessarily) observed on the Earth. Large ICMEs are large-scale, long-existing disturbances propagating in the interplanetary space; they complicate the structure of the heliomagnetosphere and are one of the factors modulating CRs. It is understood that, the more inhomogeneities (which usually carry an enhanced magnetic field) that occur in the interplanetary space, the stronger is the solar wind influence on galactic CR. Their velocity also influences the ICME efficiency: the higher it is, the higher are the density of solar wind and the intensity of interplanetary magnetic field at the front edge of the interplanetary disturbance, the stronger are the geomagnetic storms induced by the solar wind (Nikolaeva et al., 2011; Richardson et al., 2012), and the deeper are Forbush decreases (Belov, 2009; Belov et al., 2014). In view of all this, CME frequency and velocity are included in the CME-index by Mavromichalaki and Paouris (2012), and the CME-index is written as

$$Pi = 0.68N + 0.32Vp, \tag{1}$$

where N is CME number and Vp is CME mean velocity over a month.

This form of CME-index has been already mentioned in some papers presenting models of CR modulation that proved the index usability (Gushchina et al., 2012, 2014; Balabin, 2015). It might be the best of all of the indices currently used to consider the contributions of sporadic factors in long-term CR variations. Nevertheless, we believe that CME-index in form (1) still does not express all opportunities of CME observations and that it and can and must be improved. It is only natural to expect that high-velocity CMEs have the greater weight in CME-index. Therefore, we propose to include CME velocity in the index not additively, as in (1), but multiplicatively, and to replace the linear dependence on velocity with the power function. Then, instead of (1), we obtain:

$$I_{\mathrm{CME}} = \sum_{i=1}^{n} \frac{w}{360} \left(V_i/V_0\right)^b. \tag{2}$$

Here n is the CME number and V_i is the velocity of a particular CME. Parameter V_0 is measured as the velocity (hereinafter we consider V_0 = 400 km/s), and parameter b is selected such that CME-index is the most efficient. There are some other methodical questions that arise during calculation of I_{CME} and they deserve consideration.

1. What CME shall we consider? It is obvious that the influence of small and weak CMEs on the solar wind structure is insignificant, and thus they are not efficient (Paouris, 2013). To mitigate their influence we have added factor $w/360$, where w is the CME angular width. It would be inexpedient to consider a stronger dependence of CME on the angular width. In fact, this function shows, if it does, only the latitudinal span of a particular ejection, while the CME, which is latitudinally narrow, can feature a considerable longitudinal extension. On the other hand, an ejection registered by coronograph as a maximally wide (halo) event in the central zone of the solar disk can have rather modest real sizes (Michalek, 2006; Belov et al., 2014).

2. When the CME-index is used to compare events occurring on the Earth or near the Earth, it is necessary to bear in mind that solar wind disturbances caused by CME need 2–4 days to reach the Earth's orbit (sometimes even less than 24 hours, and this time exceeds 5 days for some ICME events). In this paper,

Table 1. Monthly CME-indices obtained from observations by Soho/LASCO during the period of 1996–2015

1996	−99.0	−99.0	−99.0	−99.0	16.8	0.5	3.7	6.5	0.8	2.5	5.8	4.1
1997	1.0	4.6	1.9	8.7	4.7	2.0	2.4	2.5	10.9	13.0	29.5	5.9
1998	13.7	8.7	37.1	51.3	56.3	52.4*	51.0*	80.8*	64.4*	43.5*	71.6*	58.6*
1999	48.0*	61.3*	15.2	31.3	55.4	90.9	49.8	35.5	60.1	30.5	38.7*	36.3
2000	41.7	49.8	46.4	42.7	93.8	60.7	83.0	42.0	54.6	50.1	108.6	41.6
2001	54.9	37.3	50.2	168.8	51.1	67.2	20.5	44.6	71.7	76.5	76.6	73.6
2002	50.7	31.1	81.3	71.8	80.3	30.1	135.3	85.2	57.0	101.8	58.1	41.8
2003	34.2	24.4	41.4	39.7	58.3	61.3*	12.7	14.0	16.8	114.4	181.2	10.8
2004	50.6	12.1	12.4	37.7*	20.8	35.3	66.3	15.9	39.1*	17.4	95.7	47.0
2005	124.1	25.8	13.3	16.2	60.2	43.7	174.8	84.6	118.6	4.0	7.9	15.7
2006	9.6	4.5	4.3	8.5	11.4	6.0	11.0	12.9	13.0	4.6	39.5	26.3
2007	17.2	8.7	4.3	3.8	8.3	4.8	6.4	5.4	2.5	2.5	1.9	4.5
2008	3.9	2.8	3.7	6.0	2.6	1.9	1.8	1.3	0.7	1.7	2.4	2.1
2009	1.7	10.6*	1.5	1.4	1.5	1.9	1.6	1.5	2.3	2.0	2.2	3.1
2010	3.1	15.0	13.5	8.2	7.5	6.9	7.6	38.8	10.1	5.9	11.6	12.7
2011	11.6	16.3	58.8	30.2	31.9	64.6	16.3	43.3	89.8	48.2	56.1	43.4
2012	86.0	25.3	132.8	54.5	66.8	58.7	108.3	73.6	63.3	24.7	64.9	27.5
2013	28.8	39.3	33.1	40.2	104.3	54.1	27.0	38.4	29.7	79.3	67.6	68.0
2014	95.8	90.6	58.9	55.5	55.7	75.4	31.1	38.4	90.8	34.9	47.9	59.5
2015	20.4	30.9	62.1	59.8	48.4	67.0	28.7	23.0	24.9	21.5	55.5*	41.1*

* Indices are calculated according to the data on Forbush effects.

we did not consider the lag or shift time series, since we were primarily focused on the long-term CR variations created by the entire heliosphere.

3. Although the observations performed by Soho/LASCO were thorough enough, they were interrupted a few times for various reasons. The information on pauses made in the observations (mostly short) is included in the database http://cdaw.gsfc.nasa.gov/CME_list/. We took this information into account, assuming that some CMEs could be missed due to the pauses, so the CME index had to be increased in view of this fact. Therefore, in its final form (2), the CME index is multiplied by $c = t_m/(t_m - t_g)$, where t_m is the number of days in a month and t_g is the total number of days of all pauses in observations. If factor $\underline{c}$ is less than 0.8, the month is not considered in calculations. A single long-term pause in Soho's observations was registered in 1998–1999, when communication with the spacecraft was lost [http://cdaw.gsfc.nasa.gov/CME_list/].

4. Here we study the monthly mean indices, and a question may arise as to whether it is necessary to consider the real duration of months. It is apparently not necessary, since we are looking not for CME specific efficiency but for their integral effect.

Hence, the proposed index (see Table 1) considers the number, velocity, and angular size of CMEs. A comparatively slow (V = 400 km/s) ejection of halo type (w = 360°) makes a single contribution in $I_{\rm CME}$, and the contribution of a high-velocity CME is determined by parameter b, the selection of which we shall consider below.

4. SELECTION OF THE OPTIMUM PARAMETERS

Since we are looking for an index that allows consideration FE participation in long-term variations, FEs can be used to identify the optimal parameters. We have managed to do it using information about all FEs (since July 1957) presented in the database on FEs and interplanetary disturbances. Using the data we calculated the routine FE index I_F for each month as the total of all FEs originating in the given month, and compared the $I_{\rm CME}$ and I_F indices. Parameter b in expression (2) was selected such that the correlation factor between $I_{\rm CME}$ and I_F was maximum. For 114 months from January 1996 to October 2015, the correlation factor was 0.77 ± 0.04 at $b = 1.66$ (Fig. 1). The correlation between the two indices is strong enough. Note that, while all CMEs create FEs in the heliosphere, not all of them are observed on the Earth. On the other hand, some FEs observed on the Earth are associated with coronal holes and not with CMEs. In additional, some observed FEs are associated with CMEs not registered by coronographs (Howard and Harrison, 2012).

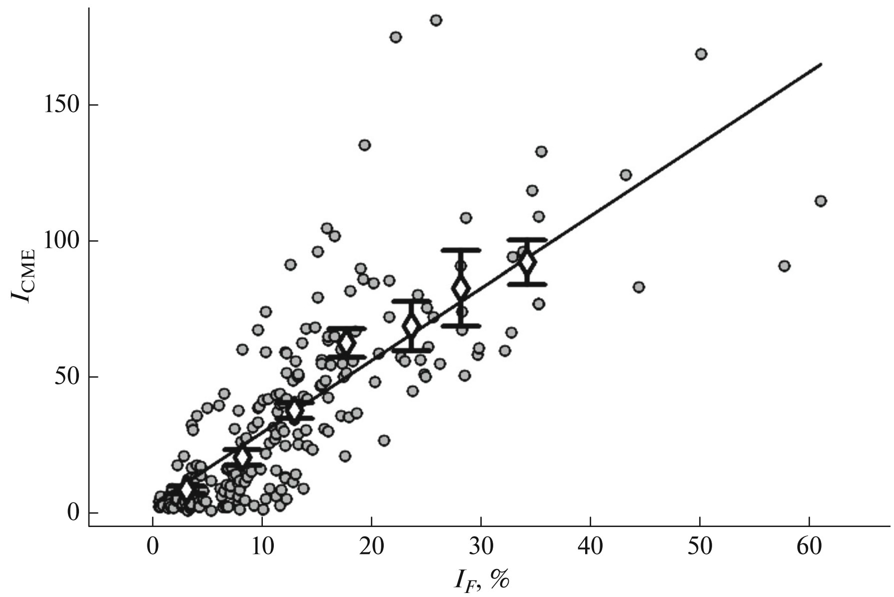

Fig. 1. Relation between the FE-index I_F and the CME-index I_{CME} during the period of 1996–2015.

5. CME-INDEX AND LONG-TERM CR VARIATIONS

The good correlation between I_F and I_{CME} provides an opportunity to use the regression relationship between the two indices (straight line in Fig. 1) to fill in the gaps in CME observations. It is a valuable opportunity, since these gaps considerably hamper the use of CMEs in long-term studies. For 16 months (June 1998–February 1999, November 1999, June 2003, April and September 2004, February 2009, November and December 2015), the CME-index was calculated by the formula

$$I_{CME} = -7.55 + 3.426 I_F \qquad (3)$$

which matches the linear regression and orthogonal option of the least squares method. Sixteen months make a small part of the total number of 230 months, so they do not prevent I_{CME} from being the CME-index. It is fair to note that, at small values of I_F, expression (3) does not allow a reasonable value of I_{CME}. Therefore, Eq. (1) needs to be complemented with limitation $I_{CME} = 0$ when (3) gives a negative value. Such months were few, and all of them pertained to the period of 2006–2009, i.e., to the period of abnormally low minimum of solar activity.

The corrected I_{CME} index was used in the model of long-term CR modulations to replace the sporadic solar phenomenon indices applied earlier: the X-ray flare index *xf*, the number of geomagnetic storm sudden commencements N_{SSC}, and the *Pi* index introduced by Mavromichalaki and Paouris (2012).

In this paper, we are not focusing of details of the model presented earlier (Belov et al., 2002; Gushchina et al., 2008). We only note that, along with the CME-index, the following solar indices have been used: the inclination of the heliospheric current sheet *hcst*, the mean magnetic field of the Sun *Bss*, the dipole component of the solar magnetic field *Hpol*, and the area of low-latitude coronal holes A_l (Gushchina et al., 2016).

Hence, the description of long-term CR modulation over 1996–2015 is carried out with the model that includes five solar indices: *hcst*, *Bss*, *Hpol*, the area of low-latitude coronal holes A_l, one of the coronal indices (the selection of this characteristic of CH is based on Gushchina et al. (2016)), and the index I_{CME}.

The spectrum of long-term CR variations is calculated according to the technique proposed by Belov et al. (1993) and stipulates the identification of the isotropic component of cosmic radiation on the basis of all available information on the CR intensity obtained at its registration by the neutron monitor (NM) ground network (~40 monitors) and by stratosphere sounding at three points (Stozhkov et al., 2007). Further analysis is performed over the monthly mean amplitudes of long-term galactic CR variations for particles with a rigidity of 10 GV–*a*10, % (% compared to 2009), i.e., the particles with energy to which the neutron monitors are most sensitive.

For the abovementioned solar-heliospheric characteristics and amplitudes of long-term variations of CRs with rigidity of 10 GV (*a*10, %), a multi-parameter regression analysis is performed. In Fig. 2, the result of the model description of CR variations for the period of 1996–2015 is presented. For this period, we have high correlation coefficient $\rho = 0.96$ and root-mean-square deviation of $\sigma = 1.54\%$ for parameters A_l, *Bss*, I_{CME} and *hcst* (determined for $R = 2.5R_0$) with

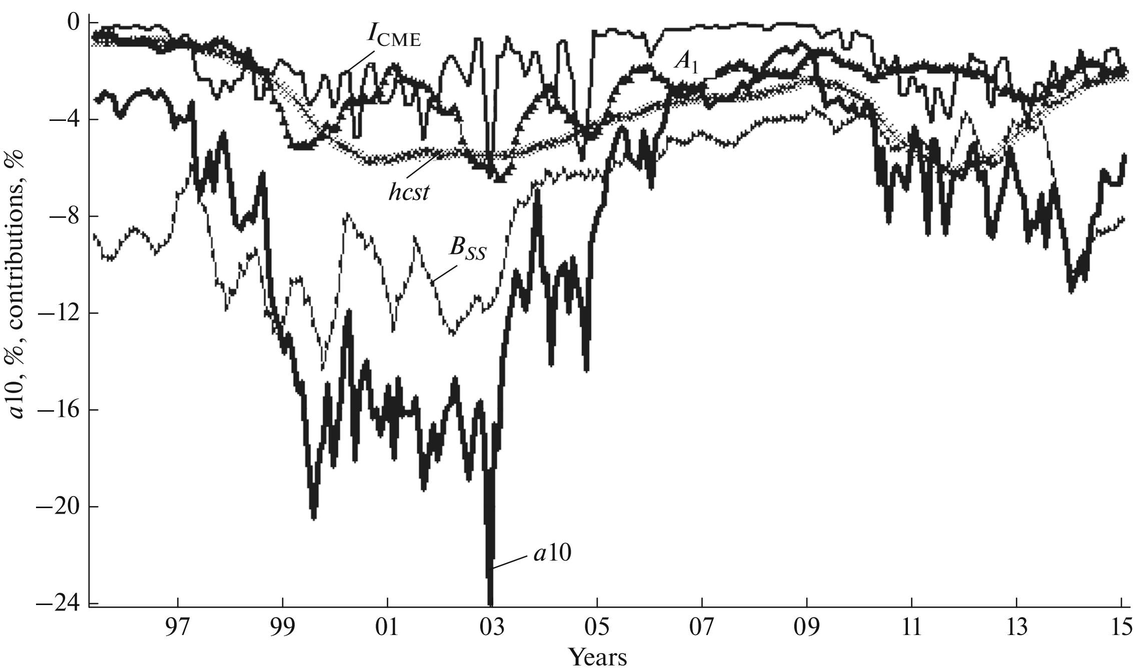

Fig. 2. CR variations (rigidity 10 GV) *a*10,% (in relation to 2009) observed from May 1996 to December 2015, and contributions of variations of SA indices I_{CME}, A_l, *hcst* and B_{SS} to the modulation.

lag times of 11, 4, 1, and 20 months, respectively, for the specified characteristics.

Using instead of I_{CME}, another CME-index, for example, *Pi*, we obtain a poorer correlation between the model and the experimental data. Hence, the I_{CME} index justifies our expectations and is suitable for the long-term simulation of CR variations. Note that, during this period (cycle 23 and part of cycle 24), the CME contribution to CR modulation is close by volume to that of coronal holes, about 6.5%. The time variations of this contribution of I_{CME} during cycle 24 are precisely reflected in the observed CR variations that describe oscillations with variable period on the background of decreasing eleven-year CR variation. For I_{CME} the lag time was the shortest (1 month) as compared with other indices. This shows that not all CMEs are essential for CR modulation; only the recent events, i.e., the CME that occur in the inner part of the heliosphere, are essential. On the other hand, it is not only CMEs (and Forbush decreases) occurring in the same month that are important for the long-term CR modulation, because, in this case, the lag would be 0 months (index description). The events of the previous month are also important. This means that, since relatively fast (and most efficient) ejections can move 6–10 AU or farther during a period of 1–2 months, all CMEs of the entire inner heliosphere have a considerable influence on CR intensity near the Earth.

At the same time, it is important to bear in mind that all other solar indices used in the modulation model feature considerably larger lags and reflect a larger-scale impact of the structure and state of the heliosphere on CR modulation.

6. EXPANDING CME-INDEX BACK OVER EARLIER YEARS

Reliable and homogeneous CR variations based on measurements made by neutron monitors have been obtained since 1953 (Belov et al., 1993). In order to get the index of sporadic solar phenomena for the entire period, we expanded the CME-index back to the years preceding the Soho mission. This can be achieved for the period starting in July 1957 and continuing to the mid-1996 with the use of the identified interrelation between the CME-index and frequency and value of FE. The relatively short period of 1953–1957, for which no reliable data about FE are available, can be filled in by means of the I_{SC} index mentioned in the Introduction, which represents the monthly number of geomagnetic storm sudden commencements N_{SSC}. According to the data for 1996–2015, the least squares method in its orthogonal option gives the following expression

$$I_{CME} = -5.2 + 20 I_{SC}, \quad (4)$$

which approximates the real data with a correlation coefficient of 0.56 ± 0.06. In this case, we can hardly expect a closer correlation, since I_{SC} does not represent either interplanetary disturbances that have missed the Earth or the I_{CME}, the velocity of which is insufficient to create an interplanetary shock wave.

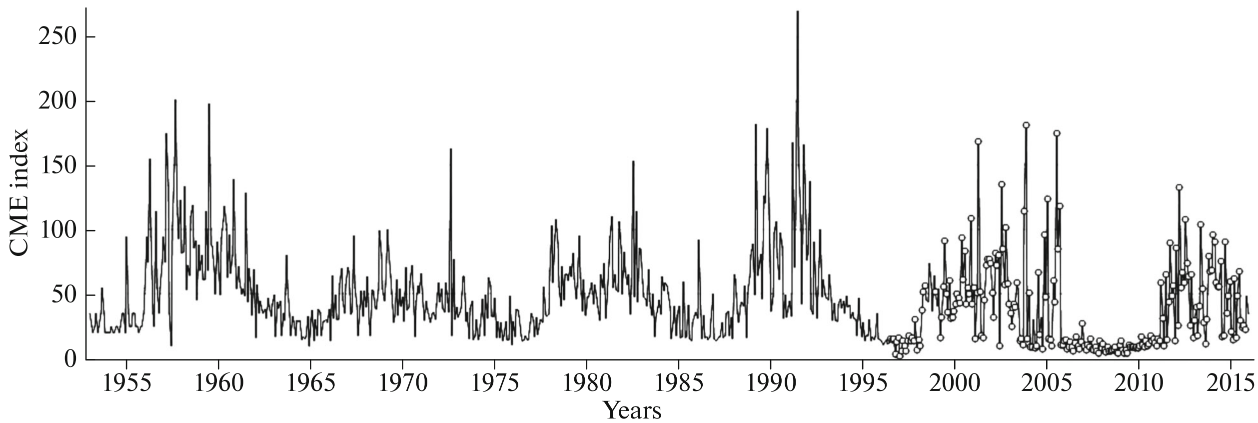

Fig. 3. Behavior of the expanded CME-index in 1953–2015. Months in which observations of Soho/LASCO coronographs were used are marked with circles.

Therefore, only a minor part of the interplanetary disturbances really modulating CRs is included in I_{SC}. For the same reason, expression (4) gives an inadequate result at small values of I_{SC}. During the months without SSC, large-scale CMEs usually arrive at the Earth or miss the Earth with even greater probability. Taking this factor into consideration, we used expression (4) for $I_{SC} > 1$, and we found then mean I_{CME} for $I_{SC} = 0$ and $I_{SC} = 1$, which appeared to be close to 19 and 24, respectively.

The expanded CME index for the whole 63-year period is shown in Fig. 3. As expected, a quasi-11-year cycle of solar activity is shown fairly well in the I_{CME} behavior . At the same time, the I_{CME} behavior is very different from the sunspot number behavior—it “surges” more and shows considerable fluctuations from month to month. The long-term period (about three years) of abnormally low levels of the CME-index during the last minimum of solar activity (2007–2009) is particularly interesting.

Certainly, the index data obtained before 1996 can be only conventionally assigned to the CME-index; nevertheless, with no better options, they can be used to study long-term variations. We expect regular observations of CMEs to continue and the number of high-grade reliable identifications of CME-index to increase.

In order to get a fuller correlation of CR modulation with variations of solar wind structures observed during the cycle of solar activity (SA) and caused by variations of relative contribution of the Sun’s magnetic fields of different scales (global and local) within the process of the cycle evolution, a description of long-term variations was performed with a combination of the indices mentioned in the previous section. The CR simulation for 1957–2015 differs in the use of a simplified representation of the polar field with respect to the direction of the global magnetic field of the Sun (*Hpol* = 1, 0, −1) with consideration of the polarity reversal period. This assumption has been taken due to the lack of observational data on the solar magnetic field for such a long period.

The results of simulation of long-term CR variations for the last five SA cycles (1957–2015) are displayed in Fig. 4; they use the obtained expanded CME-index, together with other SA characteristics: *hcst*, *Bss* and A_l. It is shown that each of them make different contributions to generated modulation in different epochs of solar cycles, despite the 11-year periodicity intrinsic to contributions of all used SA characteristics. The differences are quite specific for every index and are clearly manifested, for example, in the mismatch between the maximum phases.

For the period from September 1957 to December 2015, the correlation coefficient was calculated for the four-parametric (*Bss*, expanded CME-index, *hcst* and *Hpol*) modulation model with $\rho = 0.84$ and $\sigma = 2.88\%$ and lag times 5, 2, 5, and 11 months, respectively, for the specified characteristics. We previously (before including the CME-index into consideration) used N_{SSC}, which is the number of magnetic storm sudden commencements to map short-period phenomena in the model of CR modulation with statistical characteristics $\rho = 0.81$ and $\sigma = 3.10\%$. As we see, the multi-parameter model of CR modulation with consideration of the CME index improves the description of the observed long-term CR variations.

In the paper, special attention is paid to the study of the influence of CMEs participating in the formation of solar wind inhomogeneities on the CR modulation. It was assumed to be necessary to consider more precisely (using the available modern observational data) these SA manifestations in the simulation of CR modulations.

7. BASIC CONCLUSIONS

The influence of CMEs on the status and structure of the heliomagnetosphere is the greatest of all spo-

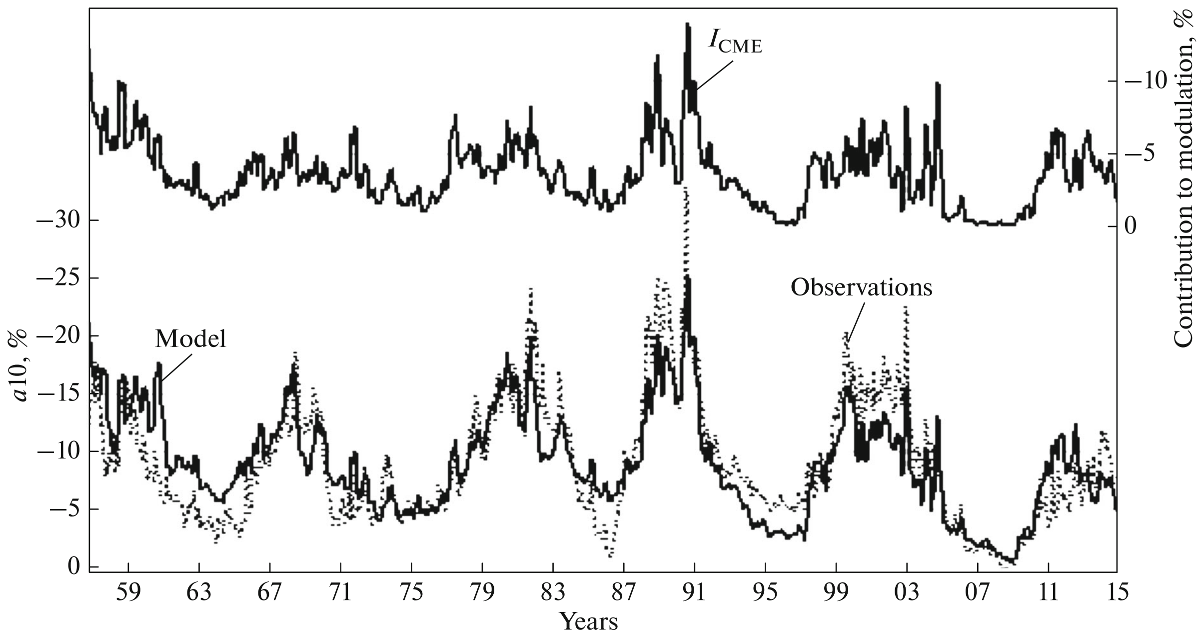

Fig. 4. Left scale: *a*10, %, long-term CR variations observed in 1957–2015 (solid curve is model; points are observed variations); right scale: contribution of I_{CME} of sporadic SA to the model of CR modulation.

radic solar phenomena. Hence, CME observations should form the basis for the creation of an index of sporadic solar phenomena aimed at long-term exploration of solar activity influences, in particular, in studies of long-term CR modulation.

Observational data accumulated by Soho/LASCO for the last 20 years provide an opportunity to create this index and to test its usability.

We have confirmed that the CME-index should be based on the CME number and velocity, and we proposed a new version.

In this paper, a good correlation of the new CME-index with the number and value of Forbush effects observed by the ground neutron monitors is shown.

The inclusion of the new CME-index in the model of long-term variations of cosmic rays has considerably improved the agreement between the calculated and the observed variations. The contribution of the CME impact to the model of CR modulation sometimes reaches 14%.

The statistical correlation of the CME-index with FEs and geomagnetic storm sudden commencements has allowed us to expand the index over the long-term period (from 1953) and to apply the new index for all years using the reliable data of the neutron monitors.

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