

Theoretical and experimental study of the 27-day variation of the galactic cosmic ray intensity for a solar wind velocity depending on heliolongitude

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Abstract. We develop a three dimensional (3-D) model of the 27-day variation of galactic cosmic ray (GCR) intensity with a spatial variation of the solar wind velocity. We investigate the influence of the first (27 days), second (14 days) and third (9 day) harmonic waves of the solar wind speed on the distribution of galactic cosmic ray intensity during Carrington rotation period. A consistent, divergence-free interplanetary magnetic field is derived by solving the corresponding Maxwell equations with a variable solar wind speed, which reproduces in situ observed experimental data. We perform model calculations for the GCR intensity using the variable solar wind and the corresponding magnetic field. Results are compatible with neutron monitors experimental data.

Keywords: cosmic rays, magnetic field, 27-day variation, solar wind

I. INTRODUCTION

Modeling of the 27-day variation of galactic cosmic ray (GCR) intensity is of interest since Richardson et al., [1] found that the recurrent 27-day variation of solar wind parameters as well as that of GCR intensities are $\sim 50\%$ larger for positive ($A > 0$) polarity epochs of solar magnetic cycles, than for the $A < 0$. Previously, it was demonstrated [2] - [6] that the magnitude of the 27-day variation of the GCR intensity is larger in $A > 0$, which is in agreement with the earlier result of Richardson et al. [1]. Recently, we demonstrated [7] - [10] that also the amplitudes of the 27-day variation of the GCR anisotropy at solar minimum are greater when $A > 0$ than when $A < 0$. It was demonstrated [14], [8] that the heliolongitudinal distribution of the phase of the 27-day variation of solar wind speed has a clear maximum for the $A > 0$, but it remains obscure for the $A < 0$. The phase distribution of the 27-day variation of solar wind speed shows that a long-lived (~ 22 years) active heliolongitudes exist on the Sun preferentially for the $A > 0$; the long-lived active heliolongitude is the source of the long-lived 27-day variation of the solar wind velocity, and afterwards, it can be considered as the general source of the 27-day variations of the GCR intensity and anisotropy. Moreover, [15] showed that the amplitudes of the 27-day variation of solar wind speed are about two times greater for the $A > 0$ than for the

$A < 0$. However, many of the papers [4], [7], [10], [8], [9], [11], [12], [13] aimed to explain results of Richardson et al. [1], the general attention was paid to the drift effect and the role of recurrent changes of the solar wind velocity, which is a crucial [8], [15], was not considered.

To properly model the 27-day variation of the GCR intensity based on Parker's transport equation [16], the spatial and time dependences of the solar wind velocity V and the interplanetary magnetic field (IMF) B must be taken into account. However, it is rather complicated problem, because the validity of the Maxwell's equation $div B = 0$ should be kept for the time and spatially dependent solar wind velocity [17]. Maxwell's equations for the IMF B have a form, e.g., [18], [19]:

$$\frac{\partial B}{\partial t} = \nabla \times (V \times B) \quad (1)$$

$$div B = 0 \quad (2)$$

where B is the IMF, V -solar wind velocity, and t - time. To solve Eqs. (1)-(2) in general is difficult, but for our purpose, these equations can be simplified for the particular electro-magnetic conditions on the Sun and in the interplanetary space. Our aim in this paper is to compose a model of the 27-day variation of the GCR intensity for the solar wind velocity depending on heliolongitude reproducing in situ measurements; we consider three time intervals corresponding to special conditions in the interplanetary space: a) 23 May - 7 September 1995 with evident 27 day variability in the solar wind velocity (27 days - I harmonic wave); b) 15 June - 3 September 1994 with apparent 14 day variability in the solar wind velocity (14 days - II harmonic wave); c) 24 August 2007 - 28 February 2008 in which sum of the first three harmonic waves (27, 14, 9 days) well approximates the solar wind speed.

II. EXPERIMENTAL DATA

The simultaneous enhancements of the quasi periodic changes of the GCR intensity and parameters of solar wind were noticed by Richardson et al., [1] for the positive polarity periods of the solar activity minimum epochs. It was shown [4], [14], [8] that the heliolongitudinal asymmetry of the solar wind speed is one of the imperative sources of the 27-day variations of the GCR

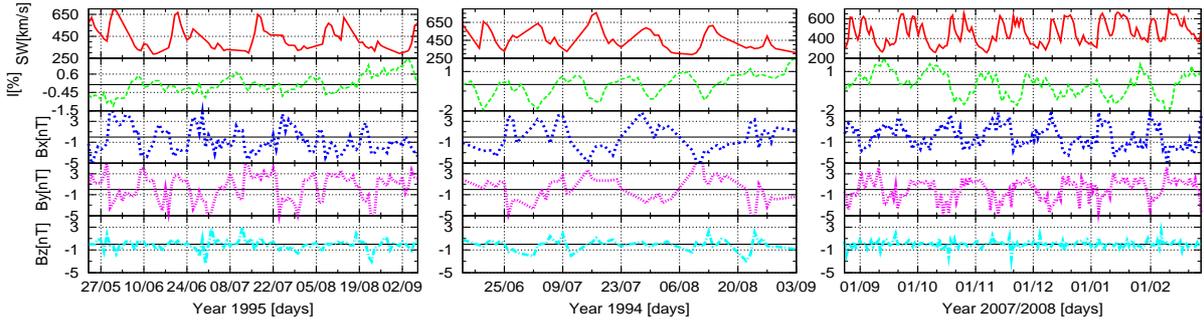


Fig. 1: abc Temporal changes of daily solar wind speed (SW) [SPIDR], GCR intensity from the Moscow neutron monitor (I) and radial Bx, azimuthal By and latitudinal Bz components of the IMF [OMNI] for the period of 23 May-7 September 1995 (left), 15 June - 3 September 1994 (middle) and 24 August 2007-28 February 2008 (right).

intensity and anisotropy in the minima epochs of solar activity. In this paper we analyze experimental data of the daily solar wind velocity, GCR intensity from the Moscow neutron monitor and radial Bx, azimuthal By and heliolatitudinal Bz components of the IMF for the three time intervals: (a) 23 May - 7 September 1995, (b) 15 June - 3 September 1994 and (c) 24 August 2007-28 February 2008. We use data of solar wind speed and IMF components from the SPIDR and OMNI data set. Fig. 1a shows that the quasi periodic changes with a period of 27 days are clearly established in all parameters except for the Bz component of the IMF. The solar wind velocity and the GCR intensity are in opposite correlation. There is not any recognizable relation of the changes of the Bz component (due to its negligible values) with other parameters; also, it is obvious that the contribution of the Bz component in the changes of the magnitude of the IMF is negligible. At the same time the solar wind velocity undoubtedly shows an existence of the first (27 days) harmonic. Fig. 1b shows that the 14 days variability (second harmonic) is evident in solar wind speed and GCR intensity remaining inversely correlated. There is not any recognizable relation of the changes of the Bz component (due to its negligible values) with other parameters; also, it is obvious that the contribution of the Bz component in the changes of the magnitude of the IMF is negligible. At the same time the solar wind velocity undoubtedly shows an existence of the second (14 days) harmonic. Fig. 1c shows that the quasi periodic changes with a period of 27 days are clearly established in all parameters except for the Bz component of the IMF. The solar wind velocity and the GCR intensity are in opposite correlation. There is not any recognizable relation of the changes of the Bz component (due to its negligible values) with other parameters; also, it is obvious that the contribution of the Bz component in the changes of the magnitude of the IMF is negligible. At the same time the solar wind velocity undoubtedly shows an existence of the first (27 days), second (14 days) and third (9 days) harmonics. Generally higher harmonics in the solar rotation period

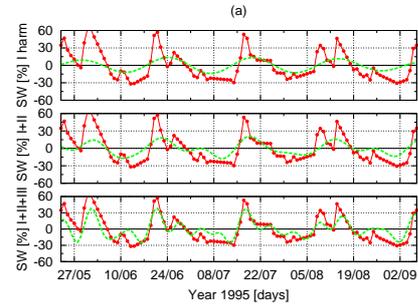


Fig. 2: Temporal changes of daily solar wind speed (solid lines) and changes of the first harmonic wave (top panel), sum of I and II harmonic waves (middle panel), and sum of I, II and III harmonic waves (bottom panel) for the period of 23 May - 7 September 1995.

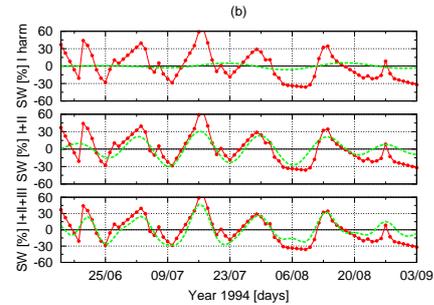


Fig. 3: As in Fig. 2 but for the period of 15 June - 3 September 1994.

(e.g. 14 and 9 days) are related with the simultaneous existence of several active heliolongitudes [20]. Recently, Temmer *et al.*, [21] provided evidence that the 9-day period in the solar wind parameters might be caused by the periodic longitudinal distribution of coronal holes on the Sun recurring for several Carrington rotations. As it was shown [4], [14], [8], the heliolongitudinal asymmetry of solar wind speed is one of the crucial parameters in creation of the 27-day variation of the GCR intensity in the minima epochs of solar activity. In connection with this, we estimate a contribution of

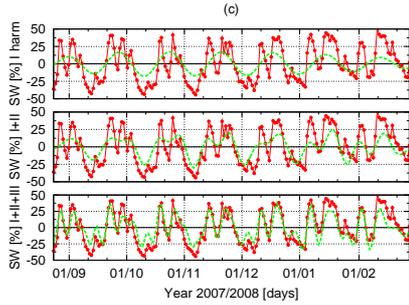


Fig. 4: As in Fig. 2 but for the period of 24 August 2007-28 February 2008.

each of the three harmonics (27, 14 and 9 days) in the daily changes of the solar wind velocity in each analyzed time interval. In this purpose we determine the best fit sine wave to each group of data using frequency filter method [22]. This technique decomposes a time series into frequency components. We use band pass filter characterized by two period (frequency) bounds and transmits only the components with a period (frequency) within these bounds. A band-pass filter rejects high and low frequencies, passing only signal around some intermediate frequency. The frequency-domain behavior of a filter is described mathematically in terms of its transfer function or network function. This is the ratio of the Laplace transforms of its output and input signals. We investigate periodicity bound within 24-32 days (27-28 days in the middle) for the I harmonic, 11-17 days (14 days in the middle) for II harmonic and 6-12 days (9 days in the middle) for III harmonic of the 27-day wave. Presented in Figs. 2-4 are temporal changes of solar wind speed corresponding to each of the three analyzed time intervals, respectively and the first (27 days) harmonic wave (upper panels), sum of the first (27 days) and the second (14 days) harmonic waves (middle panels), and sum of the first (27 days), second (14 days), and third (9 days) harmonic waves (bottom panels). For each of three analyzed periods temporal changes of each parameter are similar (quasi steady) from one Carrington rotation to another. So, the changes of the solar wind velocity, the GCR intensity, B_x , B_y , B_z components of the IMF with the solar rotation period can be considered as a quasi stationary. Value of B_z component of the IMF oscillates near zero in comparison with the changes of the B_x and B_y components so its role could be abandoned in further consideration, as well. Correlation between the changes of solar wind speed and the GCR intensity during each period to be analyzed is negative and corresponding correlation coefficients equal -0.61 for 23 May-7 September 1995, -0.72 for 15 June-3 September 1994 and -0.53 for the period of 24 August 2007-28 February 2008. This high anticorrelation shows the importance of the heliolongitudinal dependence of the solar wind velocity in creation of the 27-day variation of the GCR intensity related with Sun's rotation period.

III. MODEL OF THE 27-DAY VARIATION OF THE GCR INTENSITY

The changes of the solar wind speed, GCR intensity and components of the IMF are quasi stationary for each time interval to be analyzed. So, we assume that $\frac{\partial B}{\partial t} = 0$. We also accept that average heliolatitudinal component of solar wind speed V_θ equals zero. The latitudinal IMF component B_θ is very weak for each period to be analyzed, so we can assume that it equals zero. This assumption straightforwardly leads (from Eq. (1)) to the relationship between B_r and B_φ , as, $B_\varphi = B_r \frac{V_\varphi}{V_r}$, where V_r is solar wind speed and $V_\varphi = -\Omega r \sin\theta$ is the negative corotational speed. Then Eq. (2) with respect to the radial component B_r has a form:

$$A_1 \frac{\partial B_r}{\partial r} + A_2 \frac{\partial B_r}{\partial \varphi} + A_3 B_r = 0 \quad (3)$$

Coefficients A_1 , A_2 and A_3 depend on V_r and V_φ . Our goal is to solve Eq. (3) in heliocentric coordinate system (r, θ, φ) with a variable solar wind speed, which reproduces in situ measurements in the interplanetary space for each time interval to be analyzed. We demonstrated (Fig. 2-4) that the sum of three harmonics (27, 14, 9 days) sufficiently describes the temporal changes of the solar wind velocity during considered periods. Presented in Fig. 5 are the averaged values of solar wind speed by means of daily data (points) and dashed curve representing the approximation of the sum of three harmonic waves for each of the three periods to be analyzed, respectively. We include in Eq. (3) approximation of the changes of the average solar wind speed calculated from the experimental data for each considered time interval according to the formula (Fig. 5):

$$V_r = 400(1 + \alpha_1 \sin(\varphi - \varphi_1) + \alpha_2 \sin(2(\varphi - \varphi_2)) + \alpha_3 \sin(3(\varphi - \varphi_3))) \quad (4)$$

For (a) 23 May-7 September 1995 $\alpha_1 = -0.2342$, $\alpha_2 = 0.0622$, $\alpha_3 = -0.0725$, $\varphi_1 = 2.8$, $\varphi_2 = 2.8$, $\varphi_3 = 3$;
 (b) 15 June - 3 September 1994 $\alpha_1 = 0.1056$, $\alpha_2 = 0.2037$, $\alpha_3 = 0.0284$, $\varphi_1 = 0.7$, $\varphi_2 = 0.5$, $\varphi_3 = 0.75$;
 (c) 24 August 2007-28 February 2008 $\alpha_1 = 0.2275$, $\alpha_2 = -0.0925$, $\alpha_3 = 0.106$, $\varphi_1 = 0.5$, $\varphi_2 = 0.9$, $\varphi_3 = 0.15$. We solve Eq. (3) by numerical method. Details of this solution are discussed in [23]. For modeling of the 27-day variation of the GCR intensity we use stationary ($\frac{\partial N}{\partial t} = 0$) Parker's transport equation [16]:

$$\nabla_i (K_{ij} \nabla_j N) - \nabla_i (V_i N) + \frac{1}{3} \frac{\partial}{\partial R} (NR) (\nabla_i V_i) = 0$$

Where N and R are density and rigidity of cosmic ray particles, respectively; V_i -solar wind velocity, K_{ij} the anisotropic diffusion tensor of galactic cosmic rays. Details of this model are also discussed in [23]. Changes of the relative density obtained as a solution of transport equation for the three models of the 27-day variation of

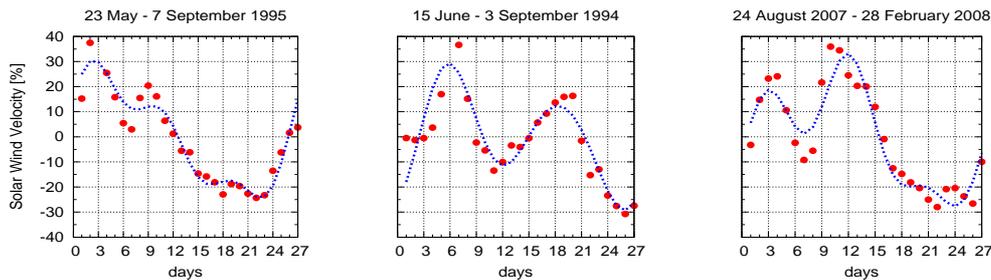


Fig. 5: Superimposed temporal changes of daily solar wind speed (points) and dashed curve representing the sum of three harmonic (27, 14 and 9 days) waves for one Carrington rotation.

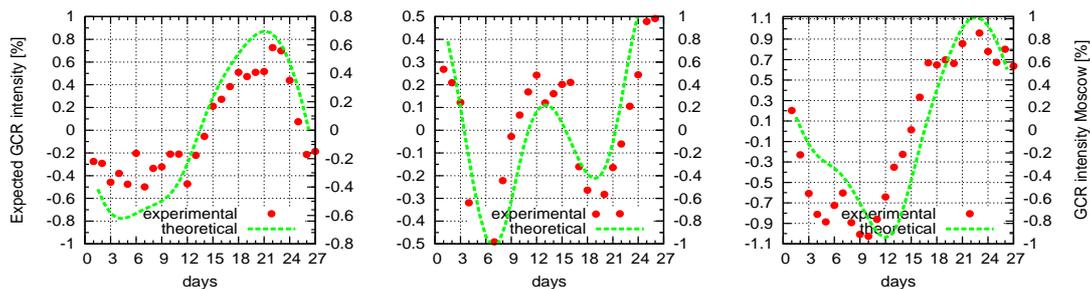


Fig. 6: Heliolongitudinal changes of the expected GCR intensity for rigidity 10GV at the Earth orbit during solar rotation period (dashed line) and temporal changes of superimposed GCR intensity from the Moscow neutron monitor (points).

the GCR intensity corresponding to the three analyzed periods are presented in Fig. 6 (dashed line); in these figures are also presented (points) changes of the GCR intensity obtained by Moscow neutron monitor averaged for (a) 4 Carrington rotations during the period of 23 May-7 September 1995, (b) 3 Carrington rotations during the period of 15 June - 3 September 1994 and (c) 7 Carrington rotations during the period of 24 August 2007-28 February 2008 (Fig. 1, respectively), as well. Fig. 6 shows that results of theoretical modeling (dashed line) and the experimental data (points) are in good agreement. We underline that the presented models of the 27-day variation of the GCR intensity composed for the changeable solar wind speed (4) and the components B_r and B_φ of the IMF obtained as the solution of Eq. (3) are compatible with the neutron monitors experimental data.

IV. CONCLUSIONS

- 1) The Maxwell equations are solved with a solar wind speed varying in heliolongitude in accordance with in situ measurements, and the longitudinal dependence of the B_r and B_φ components of the IMF are derived for the three considered periods.
- 2) Three-dimensional models are proposed for the 27-day variation of GCR intensity in response to a realistic variation of the solar wind velocity. The models incorporate the B_r and B_φ components derived from solving the Maxwell equations.

- 3) The proposed models of the 27-day variation of the GCR intensity are in good agreement with the observational material.

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