Short period changes in rigidity spectrum during the sporadic and recurrent changes of GCR intensity

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Abstract: We study hourly changes in the rigidity spectrum of the recurrent and anomaly diurnal variations of the galactic cosmic ray (GCR) intensity based on the hourly data of the worldwide neutron monitor stations. We calculate the rigidity spectrum for each hour of the recovery phase of the sporadic Forbush decrease (anomaly diurnal variations) in September 2005 and during the period of Jun - September 1994, when clearly is dominated ~ 14 days cycling expressing the second harmonic of the 27-day variations of GCR. Firstly recognized this phenomenon shows that the turbulence of the interplanetary magnetic field (IMF) can be significantly changed in short periods (during one day time), as well.

Keywords: Forbus decrease, 27-day variation of GCR intensity, anomaly diurnal variation, rigidity spectrum.

1 Introduction

One of the most recognized short periods variation of the galactic cosmic ray (GCR) intensity is the 27-day variation. General cause of the 27-day variation of the GCR intensity could be the heliolongitudinal asymmetry of the solar wind and solar activity’s parameters, especially of the solar wind velocity [1]. Thus, the heliolongitudinal asymmetry of the solar wind and solar activity’s parameters causing the 27-day variation of the GCR intensity should not have sharp lateral borders, i.e. that they are sinusoidal like [2, 3, 4]. However this is slightly idealized picture. Essentially, the 27-day variation of the GCR intensity is caused by complex distribution of the active heliolongitudes depending on solar activity [5, 6, 7, 8, 9]. Few active regions on the Sun with various power lead to the creation of the first (27-days), second (13-14 days) and third (9 days) harmonics of the 27-day variation of the GCR intensity.

Specific roles of the 27-day recurrence of the GCR intensity play Forbush decreases (FDs). This kind of changes was recognized for the first time by [10]. FDs could be divided in two kinds, sporadic and recurrent. The sporadic FD of the GCR intensity (with the amplitudes > 5 – 10% for the rigidity of 10 GV) are clearly associated with the coronal mass ejecta (CME) which is the source of the shock waves and magnetic clouds [11, 12, 13]. The recurrent FD, which tended to be smaller than sporadic FD (< 3 – 4% for the rigidity of 10 GV), are generally related with the corotating interaction regions (CIR) in the interplanetary space [14, 15, 16, 17]. There are other key of differences. The decrease phase of the sporadic FD of the GCR intensity lasts from tens of hours up to 2 – 3 days, but recovery phase is lasting averagely 5 – 10 days; at the same time, the decrease phase for the recurrent FD is larger and comparable with the recovery phase. An average duration of the recurrent FD is large ~ 10 – 14 days and, generally, the decrease and the recovery phases of the GCR intensity are rather symmetric.

Problem of the separation of the recurrent FD and the 27-day variation of the GCR intensity is unsolved up to date [18, 19]. Intermittently, it should be expected that the recurrent FD should follow the sporadic FD taking place ~ 27 days before. Nevertheless, there can be observed a single recurrent FD related with the recurrent sharpened flow of the solar wind velocity, [20] characterized FD as stronger, with more uneven structure. Being slightly particular events differing from recurrent decreases which are characterized by a structures remaining steady for a few rotations. We think that this result deals to the sporadic like FD. Thus, the problem of the single-valued division of the 27-day variation and the recurrent FD remains open. Perhaps some different features of the rigidity spectra of the 27-day, and FD of the GCR intensity could help to shed light on this issue.

In this paper we calculate the hourly variational rigidity spectrum for the period of Jun-September 1994 when we observe series of the recurrent FDs (or second harmonic wave of the 27-day variation) and for the recovery phase of the sporadic FD in September 2005. We present that during these periods are revealed the short period variations in rigidity spectrum.

2 Rigidiy spectrum of short period variations of GCR intensity

The daily evolution of the rigidity spectrum of the FD was studied for sporadic FD in [21, 22, 23, 25] and for recurrent FD in [24]. We showed that rigidity spectrum $\delta D(R)/D(R) \propto R^{-\gamma}$ of the great majority of the FDs gradually hardens during the decreasing and minimum phases of the FD and gradually softens in the recovery phase of the FD. So, the exponent $\gamma$ of the rigidity spectrum of the FD is high ($\gamma \approx 1.1 \div 1.6$) at the beginning phase of the FD, then it is gradually decreases up to the minimum (or near minimum) of the GCR intensity ($\gamma \approx 0.2 \div 0.6$) to increase again during the recovery phase of the FD. More-
over, it was showed for FDs [21, 22, 23, 24, 25] of the GCR intensity that features of the temporal changes of the power law rigidity $R$ spectrum $\delta D(R)/D(R) \propto R^{-\gamma}$ found by data of neutron monitors (NMs) and Nagoya ground muon telescopes are related with the change of the power spectral density (PSD) of the interplanetary magnetic field (IMF) turbulence ($PSD \propto f^{-n}$, $f$ is a frequency). Namely, changes of the exponent $\gamma$ of the power law rigidity $R$ spectrum explicitly depends on the changes of the exponent $\nu$ of the $PSD$ in the range of frequency $f \sim 10^{-6} \div 10^{-5}$ Hz of the IMF turbulence, to which NMs and ground muon telescopes respond. This relationship is expected because of relation of parallel diffusion coefficient $\kappa$ on rigidity $R$ as, $\kappa \propto R^{2-\nu}$ [26, 27, 28, 29], with the exponent $\nu$ of the $PSD$ of the IMF turbulence.

As far the rigidity spectrum of GCR variation can be estimated with the arbitrary interval, limited only by the availability of the GCR data from NMs, the estimation of the IMF turbulence in short time interval is questionable. The problem is that to estimate the short period temporal changes of the IMF turbulence responsible for modulation of GCR particles with rigidity $> 10$ GV we require the $PSD$ in the low frequency range i.e. $f \sim 10^{-6} \div 10^{-5}$ Hz. To fulfill this requirement we need long series of IMF data.

For that reason, if we accept relation between rigidity spectrum exponent $\gamma$ and exponent $\nu$ of the $PSD$ of the IMF turbulence i.e. $\gamma = 2 - \nu$, estimation of the $\gamma$ gives us, as a minimum a qualitative information about the state of the turbulence of the interplanetary space within any interval.
2.1 Jun-September 1994

We have calculated the variational rigidity spectrum for the each hour of the period of 14 Jun - 20 September 1994. During this period we observe clearly variation of the GCR intensity vanishes. Where $R_{0}$ = 1 GV and $R_{max}$ is rigidity beyond which the variation of the GCR intensity vanishes. To obtain a statistically reliable value for amplitudes used in the analysis, we take moving averages for 49 hours (two days). They are shown in Fig.2 (upper panel). The amplitudes for $i-th$ NM are calculated as follows:

$$J_i^k = \frac{N_i^k - N_i^0}{N_i^0}.$$  

where $N_i^k$ is the running hourly average count rate ($k = 1, 2, 3, ...$) and $N_i^0$ is the 24 hours average count rate registered on 3 September 1994. This day was chosen, as the reference day for the calculation of the amplitudes because, within the considered period, the GCR intensity registered by NMs on this day was the highest.

Applying the method in details described in [25] we have calculated $\gamma$ for each hour of day for the whole period. The 49 hours running smooth amplitudes of the GCR intensity variation in the period of 14 Jun - 13 September 1994 are presented in Fig.2 (upper panel). The corresponding changes of the rigidity spectrum exponent $\gamma$ presents bottom panel of Fig.2.

Fig.2 presents that together with the sinusoidal variation of the GCR intensity we observe the corresponding changes of the rigidity spectrum exponent $\gamma$. One can see that correspondingly to the decrease of the GCR intensity we observe the gradual hardening of the rigidity spectra, then with the increasing the GCR intensity the exponent $\gamma$ increases again (spectrum softens). This type of changes is very clear especially for the first four GCR-waves when the relative amplitude of the GCR variation is larger. This profile of changes of the exponent $\gamma$ is identical like obtain by us for different FDs, both sporadic [21, 22, 23, 25] and recurrent [24] type. This might suggest that during this period the observed GCR variation can be identified as the series of recurrent FDs. However further investigation are required.

2.2 September 2005

The sporadic FD in September 2005 was in detail analyzed in [23, 25] based on the daily neutron monitor data. We have showed that the rigidity spectrum of the FD is soft at the beginning of the FD ($\gamma \approx 1.49 \pm 0.34$) then it gradually hardens during the decreasing phase of the FD ($\gamma \approx 0.58 \pm 0.14$) and slowly softens ($\gamma \approx 1.72 \pm 0.42$) in the recovery phase of the FD. Moreover, we have provided the analysis of the IMF's turbulence and presented that during the FD we indeed observe the postulated increase of the exponent $\nu$ of the PSD of the IMF in compare with the period before and after the FD. In [25] was revealed the rigidity dependence of the exponent $\gamma$ of the rigidity spectrum of the FD on the rigidity of GCR. The rigidity spectrum exponents $\gamma$ are the larger the greater are cut off rigidities of stations used in calculations, i.e. rigidity spectrum of the GCR intensity variations during FD is hard for lower energy range and is soft for the higher energy range.

In this paper we focus on the anomaly diurnal variations in the GCR intensity observed during the recovery phase of this FD. We have calculated the variational rigidity spectrum for the each hour of the period of 11- 20 September 2005 based on the NMs data divided in three groups based on their geographical localization.

In general estimation of the rigidity spectrum of diurnal variation is difficult because very small amplitudes of the
11-20 May 2005 (North America); errors are shown for which increases the amplitude of diurnal variation (see upper panel) for Apatity, Kiel, Lomnicky Stit, Moscow, The ascending trend in the temporal changes of the exponent arises a question does for this wavy changes of the rigidity spectrum of IMF which express corresponding periodical changes of the rigidity spectrum exponent $\gamma$. 2. We find that energy spectrum of the anomaly diurnal variation of GCR intensity observed during the recovery phase of FD in September 2005 shows temporal changes (duration of $\sim 24$ hours). However, reasons of this changes is not completely understood yet.

Acknowledgment: We are very grateful to the providers of the neutron monitors stations data used in this study.

3 Conclusions
1. We show that $\sim 14$ days periodicity of the GCR intensity observed in 14 Jun-13 September 1994 can be related with the similar changes of IMF turbulence (by negatively correlated with $\gamma$ exponent $\nu$ of PSD of IMF). To obtain a statistically reliable value for amplitudes used in the analysis, we take 7 hours moving averages. The amplitudes were calculated with respect to the 7 hour average before the FD. Results of calculation of exponent $\gamma$ for each hour for period of 11-20 September 2005 and data used in calculation, are presented in Fig.3 for NMs stations localized in North America; in Fig.4 for NMs stations localized in East Europe and in Fig.5 for NMs stations localized in West Europe. The groups of stations were chosen this way to expose the clear diurnal variation wave without additional shifting between NMs counts.

The ascending trend in the temporal changes of the exponent $\gamma$ is connected with the softening of the spectrum of the FD (compare with Fig. 2 in [23]), while the waves superimposed on this trend corresponds to the diurnal GCR variation. All three Fig. 3, 4, 5 presents the wavy changes of the rigidity spectrum exponent $\gamma$ positively correlated with the anomaly diurnal variation of the GCR intensity. There arises a question does for this wavy changes of the rigidity spectrum of the anomaly diurnal variation are responsible the changes of the IMF turbulence as is observed for FDs, or maybe other factors contribute?

Unfortunately, there is not possible to show corresponding changes of the exponent $\nu$ of the IMF’s PSD due to lack of enough series of data to obtain the PSD in the low frequency. We present this paper at the ICRC conference as a problem for discussion. However, we are sure that the observed short period changes of rigidity spectrum are not groundless.

3 Conclusions
1. We show that $\sim 14$ days periodicity of the GCR intensity observed in 14 Jun-13 September 1994 can be related with the similar changes of IMF turbulence (by negatively correlated with $\gamma$ exponent $\nu$ of PSD of IMF) which express corresponding periodical changes of the rigidity spectrum exponent $\gamma$. 2. We find that energy spectrum of the anomaly diurnal variation of GCR intensity observed during the recovery phase of FD in September 2005 shows temporal changes (duration of $\sim 24$ hours). However, reasons of this changes is not completely understood yet.

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