

# NMDB and space weather forecasting

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## Abstract

From the creation of NMDB in 2007 and through the growth in the number of stations and the data accumulation, the ShICRA SB RAS group continuously has used its facilities. For the last years we have created a method for short-term forecasting of intense geomagnetic storms with an advance time 1-2 days. The probability of forecasting is around 80%. We have reported about the method in the previous NMDB: virtual symposium on cosmic ray studies with neutron detectors in 2020. The method is based on the global survey method that was developed in Yakutsk in 1960s and uses the world network of neutron monitors as a single multidirectional device. The method is intended to estimate hourly dynamics of cosmic ray anisotropy in free-space. Note that only with the NMDB creation we managed to implement it in real time mode. Now we started work on creating another method for space weather forecasting by measurements of cosmic ray fluctuations. For this purpose, we use 1-min data of NMDB. In the current report we present the first results of our investigation on forecasting of intense geomagnetic storms with  $Dst < -50$  nT. The results obtained indicate the possibility of developing and implementing in real time a method for predicting strong geophysical manifestations of space weather on the basis of ground-based cosmic ray measurements.

## 1. Introduction

The search for effective and timely space weather forecasting is one of the most important tasks of solar-terrestrial relationships. This is due to the fact that its change and subsequent impact on the Earth is potentially negative. First of all, this concerns geomagnetic storms, which can lead to various kinds of negative effects on technological systems as, for example, communication disruption or power grid failures. With the development of modern electronic technology and space exploration, the relevance of solving this issue is as high as ever.

Observations of the state of near-Earth outer space are traditionally carried out by direct measurements of the parameters of the interplanetary medium with various detectors installed on board spacecraft. At the same time, spacecraft, as a rule, are located in relative proximity to the Earth and are able to predict with great accuracy the manifestations of changes in space weather on Earth for about 1 hour.

In this short time, it is practically impossible to take real preventive measures of any kind. On the other hand, this is possible if, for the purposes of space weather forecasting, ground-based CR measurements are used, which, due to their long mean free paths, carry information about the properties of the interplanetary medium on large scales. A similar approach for space weather forecasting has been developed by many researchers (as an example, some of them can be mentioned (Mavromichalaki et al. 2006; Bieber et al. 2004; Kudela et al. 2000)).

Since the early 2000s we are working on developing a space weather forecasting technique based on ground-based measurements of cosmic rays (Grigoryev et al. 2011; Grigoryev et al. 2015). Thus, the creation of a database of neutron monitors installed on the worldwide network of CR stations (NMDB) in 2007, which provides real-time measurement data, allowed us to begin the practical implementation of the space weather forecasting algorithm based on the global survey method developed in Yakutsk at the end of the 1960s. In particular, some of the results of this work were presented at the previous NMDB symposium in 2020 (Gololobov et al. 2020). It was shown that the spatial-angular distribution of CR experiences changes that are typical only for periods before the arrival of geoeffective solar wind disturbances, which can lead to strong geomagnetic storms with  $Dst < -50$  nT. In this case, 1 hour CR registration data are used, and the method developed by us makes it possible to predict such storms with 80% probability.

Another approach to space weather forecasting is to use the recording CR intensity fluctuations (Grigoryev et al. 2008). CR fluctuations are understood as non-stationary variations with periods of less than 2-3 hours (with a frequency of more than  $10^{-4}$  Hz), which are observed only during large-scale solar wind disturbances. In connection with this circumstance, the present work is devoted to the development of a method for predicting space weather from ground-based measurements of CR intensity fluctuations.

## 2. CR intensity fluctuations

As established back in the 1970s, CR fluctuations arise as a result of modulation of high-energy CR fluxes ( $E > 1$  GeV) by magnetohydrodynamic (MHD) waves. In this case, the relationship between the anisotropic part of the CR distribution function and Alfvén waves was considered by Owens (1974). In this work, it was shown that the power spectra of fluctuations of CRs  $P_{CR}(v, \mu, V)$  and the interplanetary magnetic field (IMF) transverse components  $P_{B\perp}(v)$  are related by the relation:

$$\frac{P_{CR}(v, \mu, V)}{j_0^2} = C(v, \mu) \frac{P_{B\perp}(v)}{B_0^2} \delta_{\parallel}^2 \sim 10^{-6} \frac{P_{B\perp}(v)}{B_0^2}$$

where  $B_0$  is the average intensity of the IMF,  $j_0$  is the CR flux,  $V$  is the CR velocity in  $\text{cm}\cdot\text{s}^{-1}$ ,  $\delta_{\parallel} \sim U/c \sim 10^{-3}$  is the CR flux anisotropy along the magnetic field,  $U$  and  $c$  are the solar wind and light velocities,  $C(v, \mu)$  is a parameter that takes into account the nonlinear interaction near resonant frequencies,  $\mu$  is the pitch angle of the particle,  $v$  is the frequency.

On the other hand, in the work of Berezhko and Starodubtsev (Berezhko & Starodubtsev 1988) it was established that in the presence of fast magnetosonic waves (FMW) in the solar wind, which are capable of modulating the main, isotropic part of the CR distribution function, the spectra of CR fluctuations and the IMF modulus are related by the relation:

$$\frac{P_{CR}(\nu)}{j_0^2} = \left[ \frac{(\gamma+2)C_a(C_w + U\sin\varphi)}{3\pi\sqrt{2k_\perp\nu}} \right]^2 \frac{P_B(\nu)}{B_0^2} \sim (10^{-2} \div 1) \frac{P_B(\nu)}{B_0^2}$$

where the wave velocity is  $C_w = \sqrt{(C_a^2 + C_s^2)}$ ,  $C_a$  and  $C_s$  are the velocities of the Alfvén and magnetosonic waves,  $k_\perp$  is the transverse particle diffusion coefficient,  $\varphi$  is the angle between the solar wind direction and the IMF force lines.

In Berezhko & Starodubtsev (1988) it was shown for a number of events that it is relation (2) that is applicable to describe the spectrum of CR fluctuations in the frequency range above  $10^{-4}$  Hz, which is direct evidence of the generation of CR fluctuations precisely by FMS waves. Moreover, evidence was given that this type of MHD waves is generated by flows of suprathermal particles, which are often observed ahead of the fronts of interplanetary shock waves. And since they often cause strong geomagnetic storms, the very registration of CR fluctuations in ground-based detector data can be an effective predictor of these storms.

### 3. Method

To determine CR intensity fluctuations in the inertial part of the turbulence spectrum, we use 1-minute measurements. It should be noted that the huge array of measurement data from neutron monitors with high temporal resolution, accumulated by the world network of CR stations, is practically not used in any way, except for the analysis of rare cases of GLE events, and lies unclaimed. Here we use barometric-corrected 1-min data from the Yakutsk (62.02°N, 129.72°E,  $R_c=1.65$  GV) and Tixie Bay (71.60°N, 128.90°E,  $R_c=0.53$  GV) neutron monitors. These stations are part of the Russian national network of CR ground stations, whose data are transmitted to the NMDB server in real time. Both of these stations are located fairly close to the same meridian, and the asymptotic angles of arrival of particles at them coincide fairly well.

Fluctuations in CR and the interplanetary medium were analyzed using the standard Blackman-Tukey method (Blackman & Tukey 1958). In particular, for each station we calculated auto-spectra of CR power  $P_{xx}(\nu)$

$$P_{xx}(\nu) = 2\int w(\tau)R_{xx}(\tau)\cos(2\pi\nu\tau)d\tau$$

where  $R_{xx}(\tau)$  is an autocovariance function,  $w(\tau)$  is Tukey's correlation window, equal to

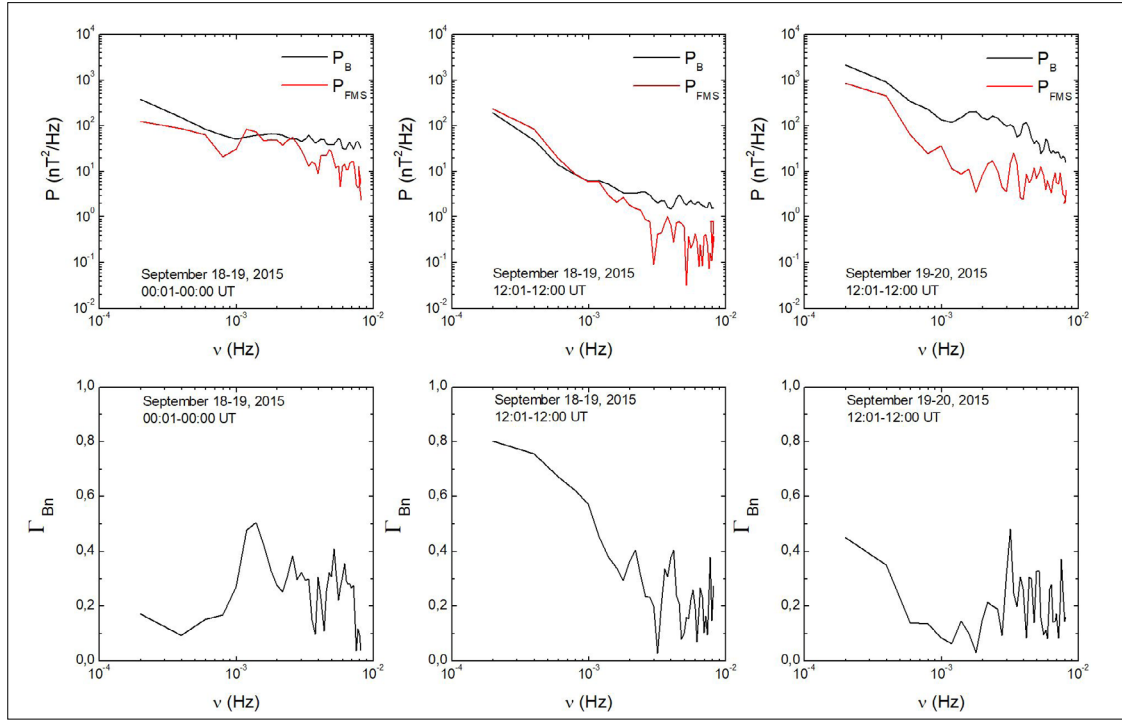
$$w_\tau(\tau) = \frac{1}{2}(1 + \cos\frac{\pi\tau}{m}), \tau \leq m$$

$$w_\tau(\tau) = 0, \tau > m$$

Also, cross power spectra of CR fluctuations were calculated for both stations. Its values can be written as the sum of the real and imaginary parts of the spectrum components:

$$P_{xy}(\nu) = C_{xy}(\nu) + j \cdot Q_{xy}(\nu),$$

where  $C_{xy}(\nu)$  and  $Q_{xy}(\nu)$  are cospectrum and quadrature spectrum.



**Fig.1:** Power spectral densities  $P_B$  and  $P_{FMS}$  as well as coherence coefficients between  $\Gamma_{Bn}$  for different time periods.

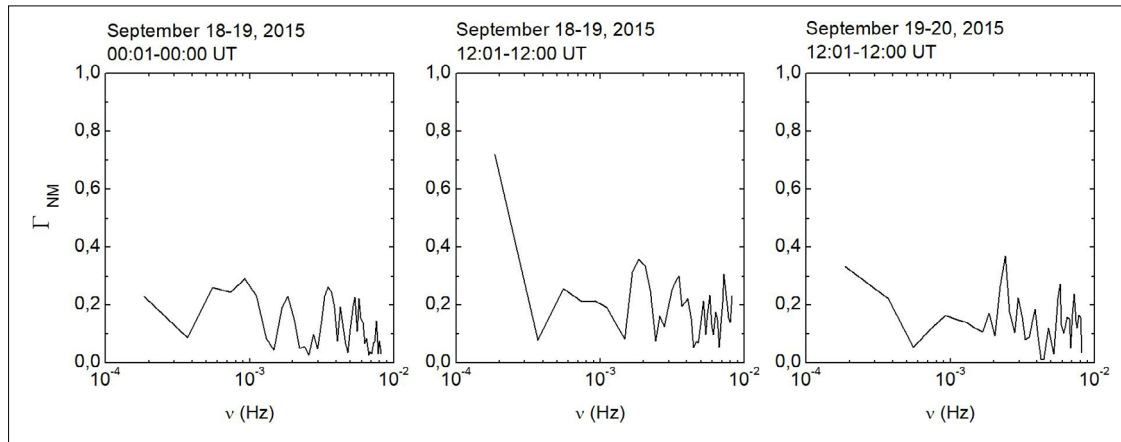
In this case, along with the spectral power of the signal, the coherence coefficient  $\Gamma_{xy}$  was determined, which determines the tightness of the connection between the fluctuations of two quantities. The coherence coefficient is defined as the positive value of the square root of the coherence function:

$$\Gamma_{xy}(\nu) = +\sqrt{\frac{P_{xy}^2}{P_{xx}P_{yy}}}$$

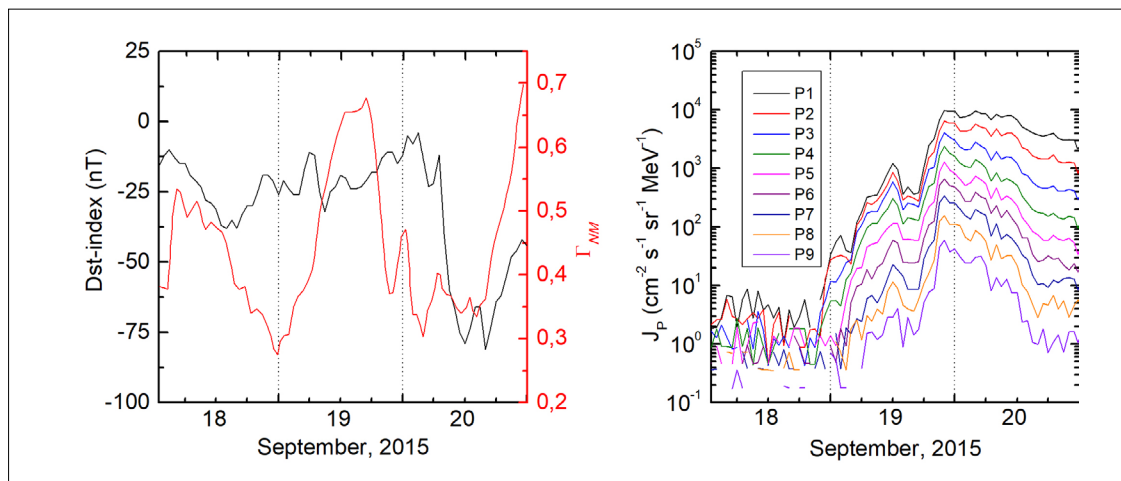
The coherence factor can also be used to determine the type of MHD wave. For example, it is known that Alfvén waves are characterized by high values of the coherence coefficient between the strength of the IMF and the solar wind velocity, FMW – between the IMF strength and the solar wind density, and slow magnetosonic waves – between the solar wind velocity and density.

## 4. Results obtained

We have analyzed more than 100 cases of observation in the 23rd and 24th cycles of solar activity of strong geomagnetic storms characterized by  $Dst < -50$  nT. Here, as an example, we will consider only one event of a strong geomagnetic storm with a  $Dst$ -index of about -80 nT that occurred on September 20, 2015. Our results are shown in Figure 1. Its analysis shows that in the time period 2015 September 18 (00:01 UT)-19 (00:00 UT), a clear increase in the coherence coefficient  $\Gamma_{Bn}$  was observed in the frequency range  $<10^{-3}$  Hz of the considered spectrum, which indicates the predominant role of FMS waves in the formation of the spectrum of IMF fluctuations.



**Fig. 2:** Coherence coefficient between CR fluctuations according to measurements of neutron monitors Yakutsk and Tixie Bay  $\Gamma_{NM}$ .



**Fig. 3.** Left panel: coherence coefficients  $\Gamma_{NM}$  and Dst-index for September 18-20, 2020. Right panel: measurement data for proton fluxes in 9 differential energy channels (P1 = 0.130-0.163 MeV, P2 = 0.163-0.233 MeV, P3 = 0.233-0.325 MeV, P4 = 0.325-0.457 MeV, P5 = 0.457-0.653 MeV, P6 = 0.653-0.884 MeV, P7 = 0.884-1.270 MeV, P8 = 1.270-1.740 MeV, P9 = 1.740-2.510 MeV) by the WIND spacecraft over a period of 18-20 September 2015.

Over the same time periods, we determined the coherence coefficients between fluctuations in the CR intensity recorded at the Yakutsk and Tixie Bay  $\Gamma_{NM}$  stations. The results obtained are presented in Figure 2. It is obvious that  $\Gamma_{NM}$  also shows high values in the low frequency region. Thus, high values of the coherence coefficient between neutron monitor stations can indicate both the presence of FMS waves in the solar wind and an impending geomagnetic storm.

Let us consider the possibility of using the coherence coefficient  $\Gamma_{NM}$  as a geomagnetic disturbance predictor. To do this, we will consider the highest values of the coherence coefficient  $\Gamma_{NM}$  in the entire spectrum range with a step of 1 hour for September 18-20, 2015. The results obtained are shown in Figure 3. As can be seen from Figure 3 (left panel), 18 hours before the storm that began on September 20, 2015, high values of  $\Gamma_{NM}$  were observed. At the same time, the results of measurements of the fluxes of super-thermal protons carried out on the WIND spacecraft (Figure 3, right panel, <https://omniweb.gsfc.nasa>.

[gov/form/sc\\_merge\\_min1.html](https://www.gov/form/sc_merge_min1.html)) show that their growth coincides with the observation of high values of  $\Gamma_{NM}$ . Consequently, superthermal protons can be a source of FMS waves.

Thus, taking into account the behavior of  $\Gamma_{NM}$  in other events, it can be assumed that it is an effective predictor of geomagnetic disturbances for medium-term space weather forecasting.

## 5. Conclusions

1. It is once again confirmed that before the arrival of interplanetary shocks at the Earth's orbit, in the inertial part of the solar wind turbulence spectra in the frequency range  $\sim 10^{-4} \div 10^2$  Hz, FMS waves of significant amplitude are often observed.
2. FMS waves are generated by fluxes of super-thermal particles with energy  $E_p \sim 1$  MeV in the vicinity of the shock front.
3. The flux of galactic CRs has been subject to modulation by FMS waves, which manifests itself in coherence as the appearance of significant CR fluctuations at frequencies  $\sim 10^{-4} \div 10^2$  Hz.
4. The results obtained indicate the possibility of developing and implementing in real time a method for predicting strong geophysical manifestations of space weather based on ground-based measurements of CR intensity.

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