Forecast of strong geomagnetic storms in February-March 2023 based on measurements of the galactic cosmic ray intensity fluctuations

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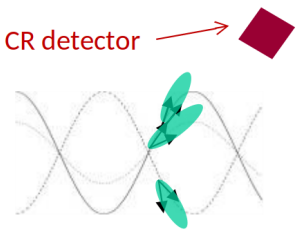
Introduction

- In order to develop methods for space weather forecasting, the dynamics of fluctuations (variations with periods from several minutes to 2-3 hours) of the intensity of GCR during the events of strong geomagnetic storms on February 26 and March 23, 2023, which are characterized by the values Dst $<$ -100 nT.
- We used 1-min data of measurements of Yakutsk and Tixie Bay neutron monitors and 1-min data of direct measurements of IMF and SW parameters by ACE and DSCOVR.
- To study the properties of CR fluctuations and SW turbulence, digital filtering methods and Blackman-Tukey spectral analysis with the Tukey spectral window are used. In this case, the maximum values of the coherence coefficients in the frequency range are used as the index of CR and SW fluctuations $1.23 \cdot 10^{-4} - 1.67 \cdot 10^{-2}$ Hz.

Nature of CR intensity fluctuations

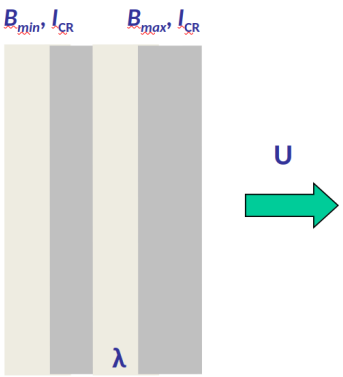
Alfwen waves [Owens A.J., Cosmic-ray scintillations .2. General Theory of Interplanetary Scintillations. J. Geophys. Res., 1974, Vol.79, P. 895-906.]



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

The oscillation of the IMF field lines leads to fluctuations in the anisotropic part of the CR intensity, which are recorded in a fix direction. It is important that the CR anisotropy $\delta_{\parallel} << 1\%$

Fast magnetosonic waves [Berezhko E.G. and Starodubtsev S.A., Nature of the dynamics of the cosmic-ray fluctuation spectrum. Izvestia AN SSSR, Ser. Fiz. 1988, Vol. 52, P.2361-2363. (In Russian)]



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

A stationary observer "sees"fluctuations of the isotropic part of the CR intensity with a period $T = \lambda/U$. It is very important that the isotropic part of the CR intensity is much larger than the anisotropic part!

Nature of CR intensity fluctuations

The linear theory of MHD waves in plasma establishes their basic properties according to which [Neugebauer et al., 1978; Toptygin, 1983]:

- a high degree of correlation (or coherence) between IMF strength B and SW velocity U (Γ_{BU}) suggests the presence of Alfvén waves in the observed SW turbulence spectra;
- between B and SW density n (Γ_{Bn}), fast magnetosonic waves;
- and between SW velocity U and density n (Γ_{Un}), slow magnetosonic waves.

Spectral analysis method

One-sided power spectral density is defined as:

$$P_{xx}(\nu) = 2\int_0^m w(\tau)R_{xx}(\tau)\cos(2\pi\nu\tau)d\tau,$$

R_{xx} is the autocovariance function, $w_T(\tau)$ is the Tukey's correlation window.

Cross-spectrum is defined as:

$$P_{xy}(\nu) = C_{xy}(\nu) + jQ_{xy}(\nu)$$
$$|P_{xy}(\nu)| = \sqrt{C_{xy}^2(\nu) + Q_{xy}^2(\nu)}$$

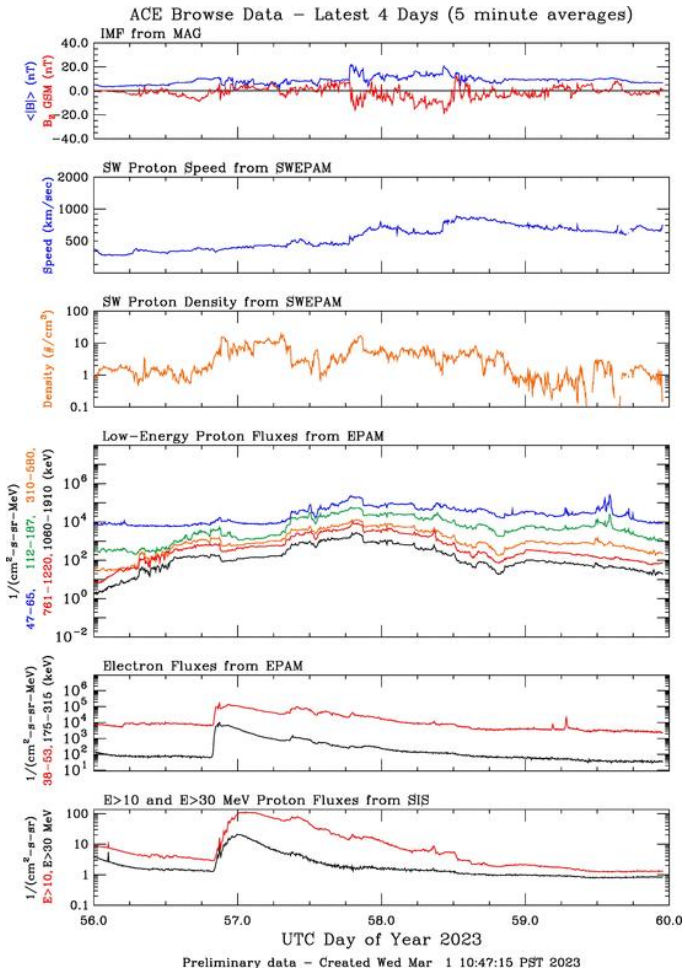
Coherence coefficients $\Gamma_{xy}^2(\nu)$ is defined by:

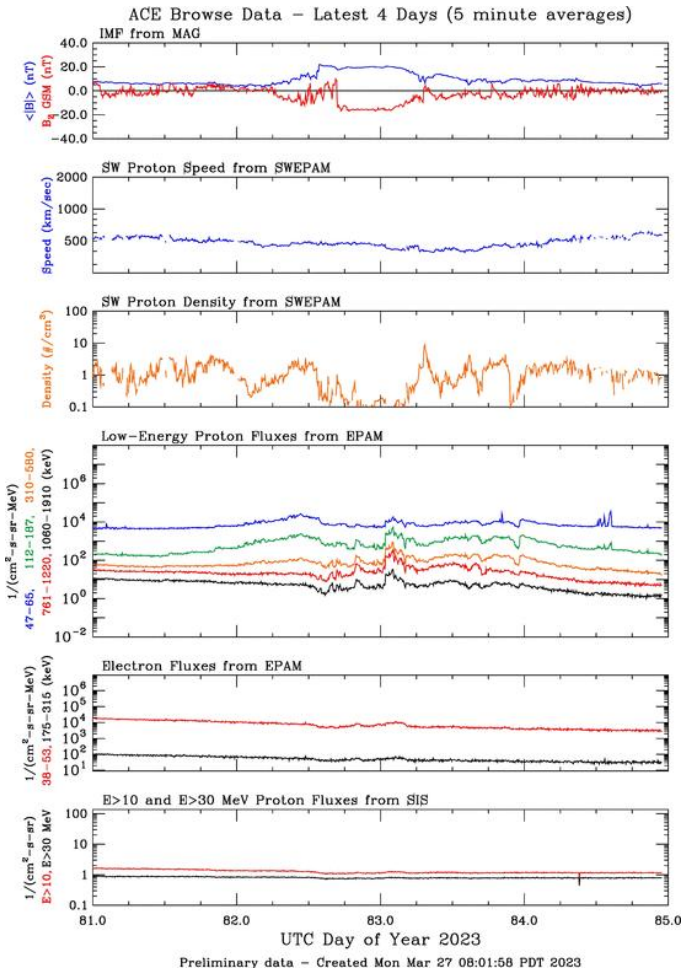
$$\Gamma_{xy}^2(\nu) = |P_{xy}^2|/(P_{xx}(\nu)P_{yy}(\nu)),\ 0 < \Gamma_{xy} < 1$$

The coherence coefficient is a generalization of the correlation function to the frequency domain.

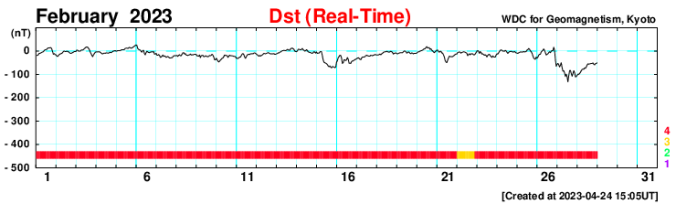
More detailed description of the method can be found in [Starodubtsev et al. Solar-Terrestrial Physics, V.9, Iss. 2, 2023]

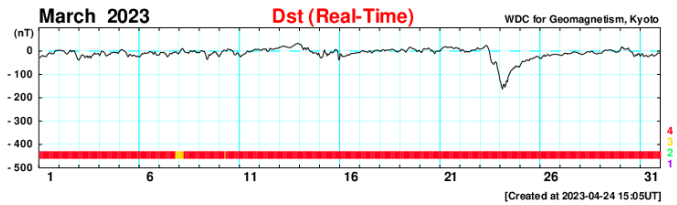
IMF and SW parameters direct measurements





[https://izw1.caltech.edu]





[https://wdc.kugi.kyoto-u.ac.jp]

Large-scale SW disturbances of such different nature caused strong geomagnetic storms!

CR fluctuations observed with ground-based CR detectors

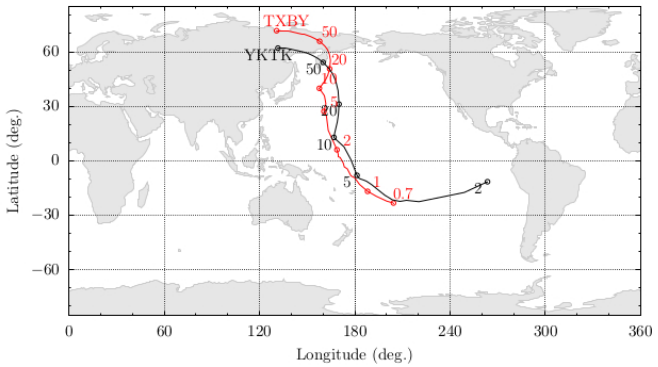
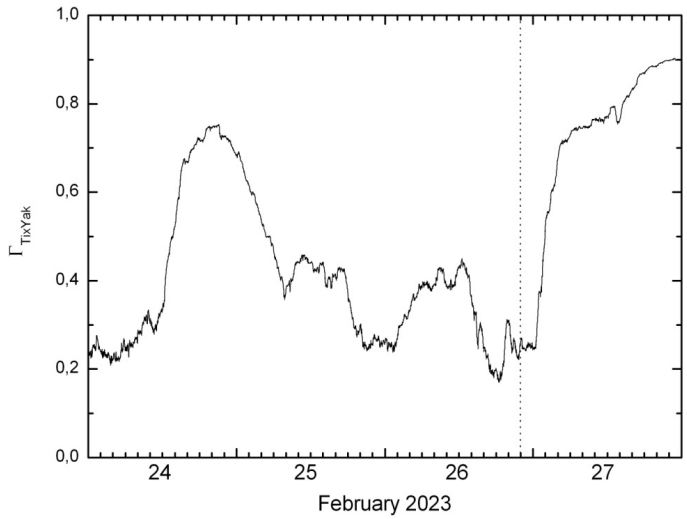


Fig. Viewing cones of CR station Yakutsk and Tixie Bay. The number are energies of CR in GeV



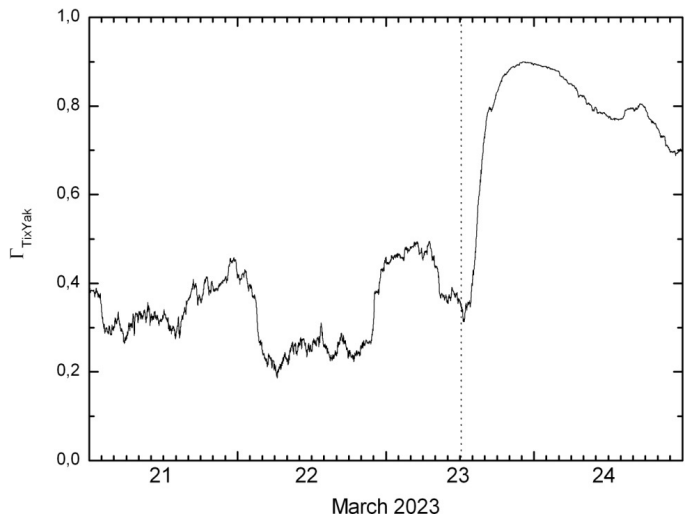


Fig. Dynamics of max values of coherence coefficients of GCR measurements in Yakutsk and Tixie Bay. The dotted lines indicates SSC.

Impact of FMSW during the events

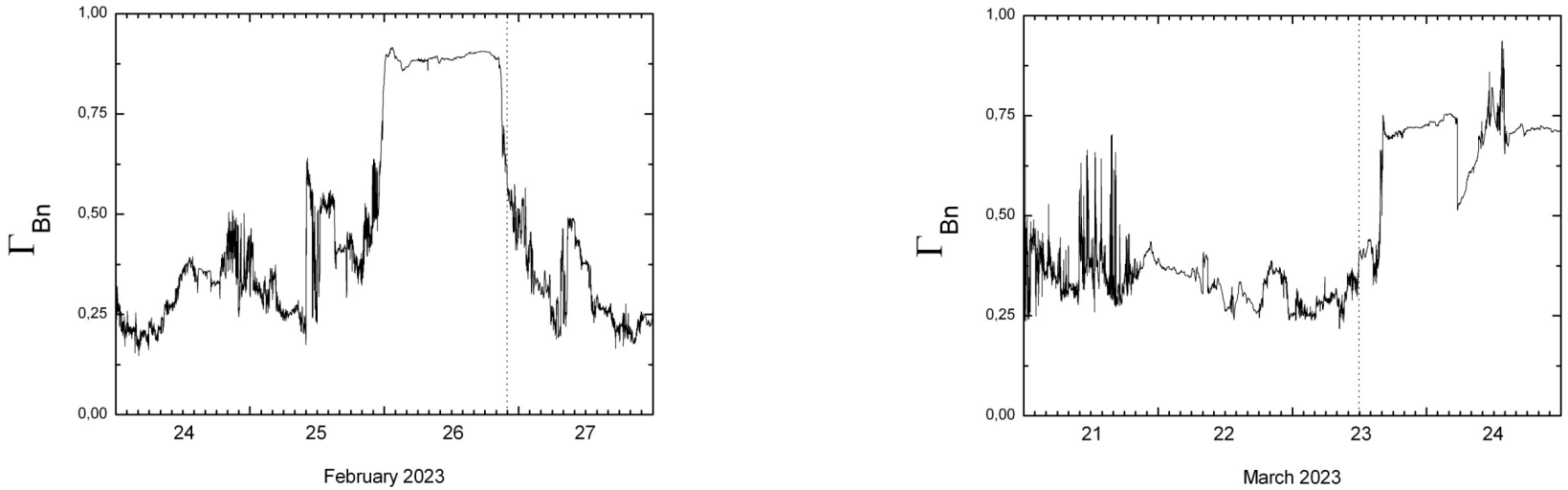


Fig. Dynamics of the maximum values of coherence coefficients for fluctuations of the IMF modulus and SW density. The dotted line shows the beginnings of geomagnetic storms.

Conclusions

- An analysis of the obtained results shows that the presence of CR fluctuations in February is due to the presence in the SW of fast magnetosonic waves of noticeable amplitude, which can be generated by storm particle fluxes in the region ahead of the interplanetary shock wave front.
- In March 2023, the contribution of these waves to the observed IMF turbulence spectrum did not exceed 50%, and no coherent CR intensity fluctuations were observed before the geomagnetic storm.
- In the region of the SW disturbance itself, high Γ_{Bn} values of CR fluctuations were observed in both events, which may indicate an increased level of magnetosonic turbulence in the region of the disturbance itself.
- The results obtained here are in good agreement with the physical picture of the occurrence of CR intensity fluctuations that we have previously constructed, but further research is required to develop a method for predicting geomagnetic storms based on measurement data from neutron monitors.

THANK YOUR FOR ATTENTION!

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