NMDB Meeting 2025: Cosmic Ray studies with Neutron Detectors

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The Severe Geomagnetic Storm G4 Observed on 10-11 October 2024

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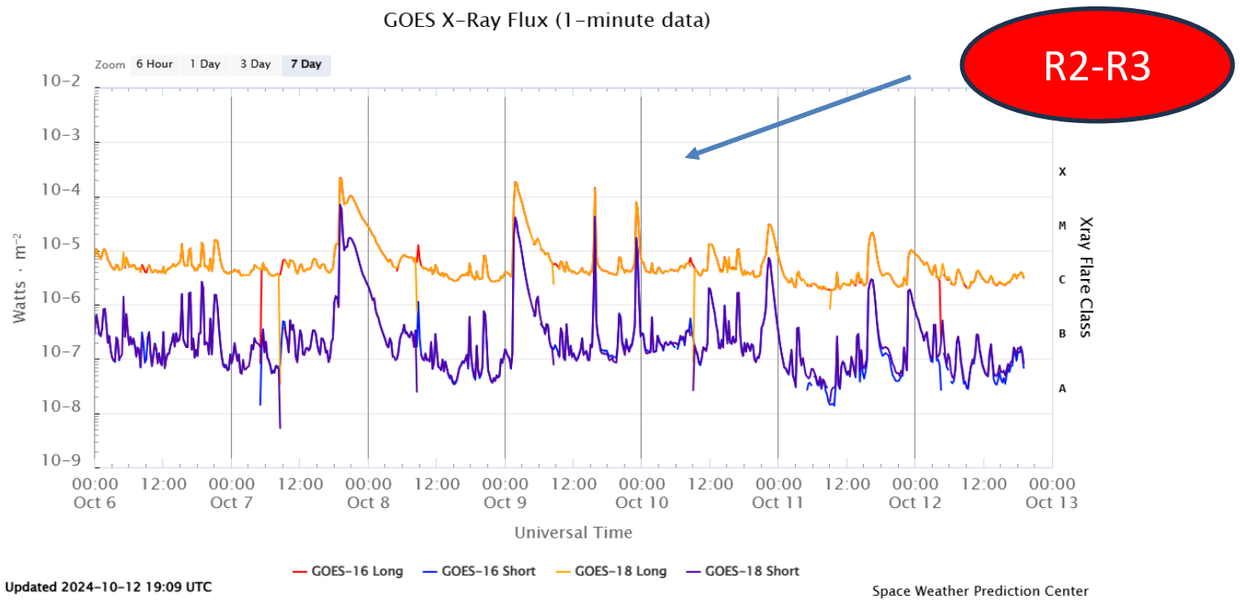
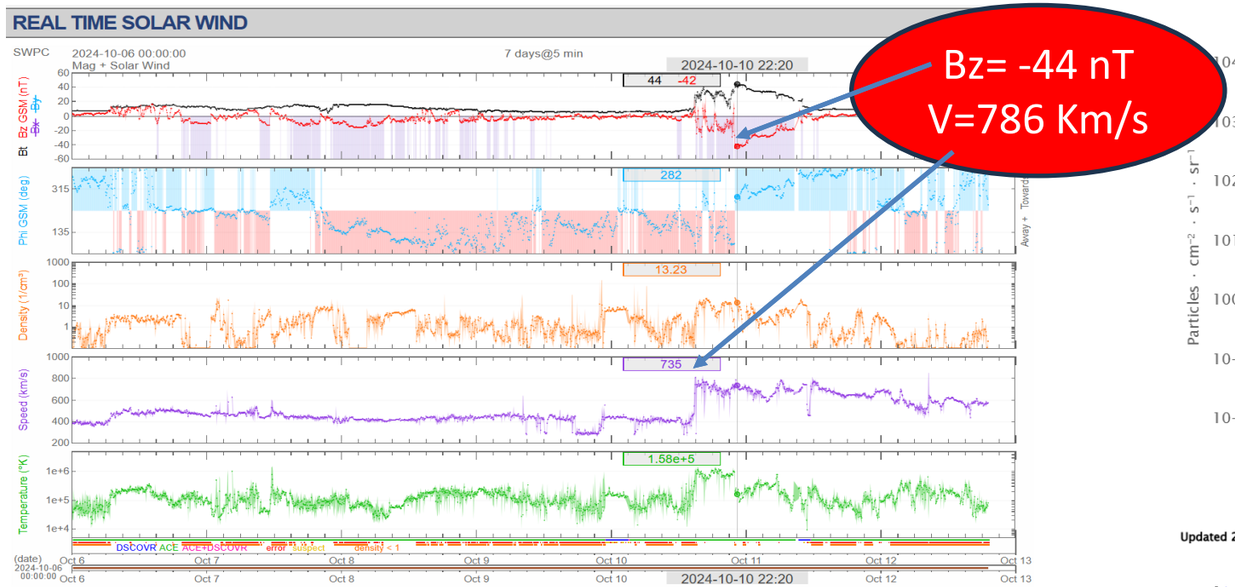
1. Introduction ‘The Severe Geomagnetic Storm G4 Observed on 10-11 October 2024’

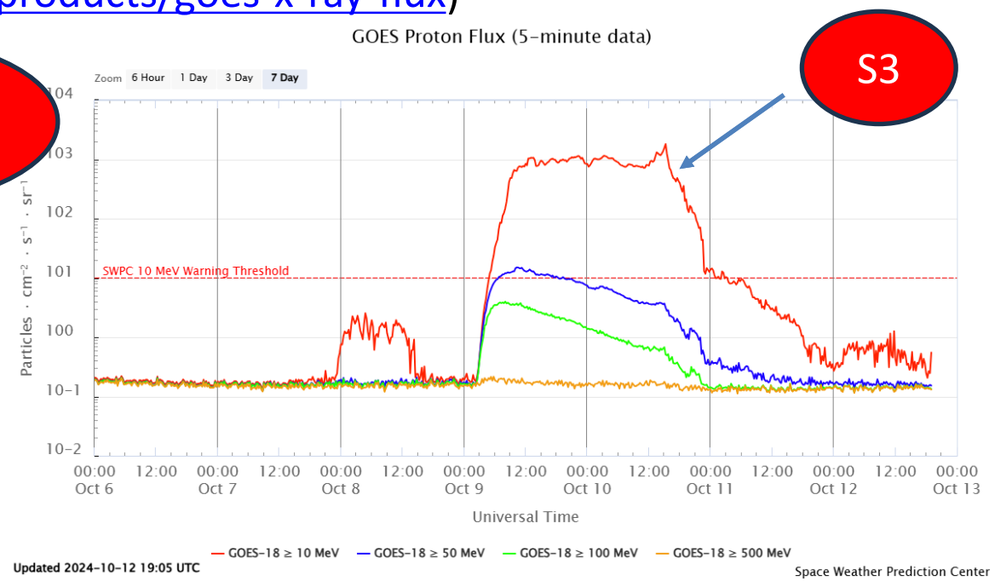
- This storm was noticed due to the effects of the CME that was observed on the Sun on October 09, 2024 at 02:12 UT (CME Scoreboard (nasa.gov)), associated with an X1.8 class flare.



(http://www.swpc.noaa.gov/products/goes-x-ray-flux)



(http://www.swpc.noaa.gov/products/real-time-solar-wind)



(http://www.swpc.noaa.gov/products/goes-proton-flux)

2. Materials & Methods

Method of Alania and Wawrzynczak (2012)

➢ The cosmic ray intensity of the Fd in free space A_i^k is given as equation:

$$A_i^k = J_i^k / \int_{R_i}^{R_{max}} \left(\frac{R}{R_0}\right)^{-\gamma^\kappa} w_i\,(R_i h_i) dR \quad \textbf{(1)}$$

➢ The cosmic ray intensity A_i^k of the Fd in the heliosphere was calculated for discrete values of γ ranging from 0.1 to 2 with step 0.01 using Matlab program (201 values) for 'i' neutron monitors.

➢ An acceptable γ_0^κ corresponds in the value which cosmic ray intensity A_i^k being almost the same for all selected neutron monitors.

(Alania, M. and Wawrzynczak, A., Adv. Space Res., 50, 2012)

A. Coupling function based on the Quantum Field Theory (Xaplanteris et al. 2021)

➢The coupling function of QFT depending on Rigidity R (GV) is defined as equation (2):

$$\boldsymbol{W(R) = 1.65 * 10^{-2} \frac{1}{R^3} [ln\left(\frac{\sqrt{R^2+1}}{R_{cut}}\right)]^2 [\frac{5}{1-0.095 \ln(\frac{\sqrt{R^2+1}}{R_{cut}})}]^2} \quad \textbf{(2)}$$

- Rcut = 1.67 GV is the Rigidity cut – off of the NMs station

(Xaplanteris et al., Solar Phys., 296, 2021)

B. Coupling function of Clem and Dorman (2000)

$$W_T(R_C,h) = \alpha(h)\,(k(h)-1)\,\exp(-\alpha(h)\, R_c^{-k(h)+1} R_c^{(-k(h))} \quad \textbf{(3)}$$

- **Solar minimum:**

  lna = 1.84+0.094 h-0.09exp(-11h)

  k=2.40-0.56h+0.24exp(-8.8h)

- **Solar maximum:**

  lna = 1.93+0.15 h-0.18exp(-10h)

  k=2.32-0.49h+0.18exp(-9.5h)

(Clem and Dorman, Space Sci. Rev., 93, 2000)

2. Materials & Methods

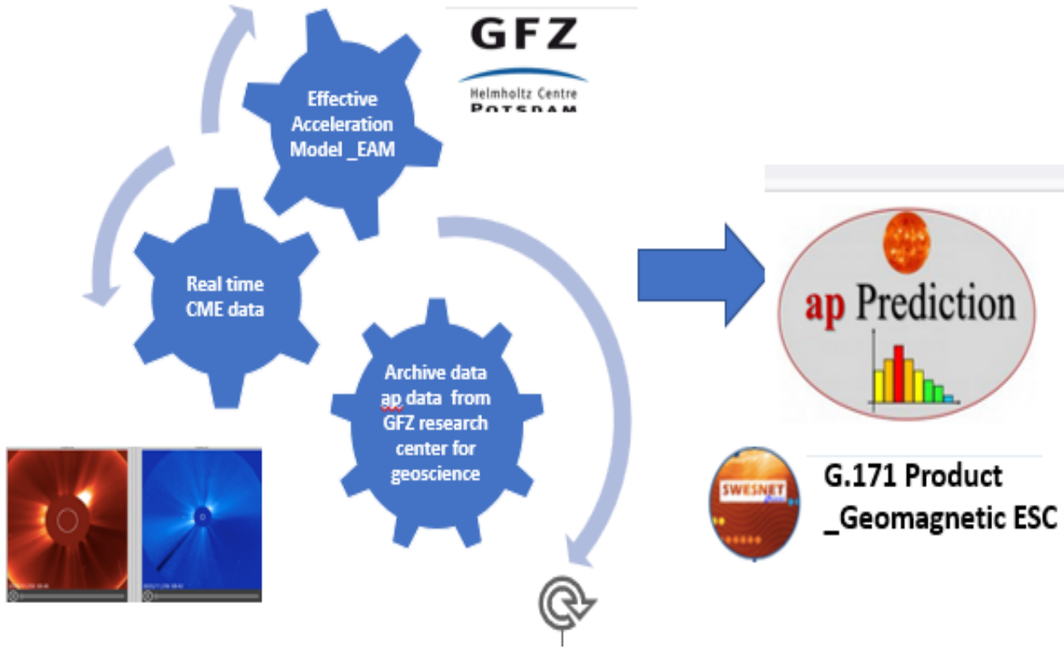


Figure 1. Block diagram of ap prediction tool (*https://swe.ssa.esa.int/ap_Prediction-federated*, accessed on 1 July 2024)

(*Mavromichalaki et al., Atmosphere, 15, 2024*)

- ✓ The aim of the "ap Prediction" tool (G.171 product) is to forecast the values of the ap geomagnetic index for the next 72 h with a 3 h prediction interval.
- ✓ This product is utilizing the archived time series of the ap index with a 3-hour time interval resolution based on archived data of the solar cycles 23 and 24 to train the Long short-term memory (LSTM) model and predict the future values (forecasts).
- ✓ In case of **Coronal Mass Ejection** (extreme Space Weather events) the algorithm imports all the need data and parameters for this CME event (i.e velocity, angular width etc) and estimates the maximum value of the ap index and the time of arrival.

https://apprediction.phys.uoa.gr/

3. Results

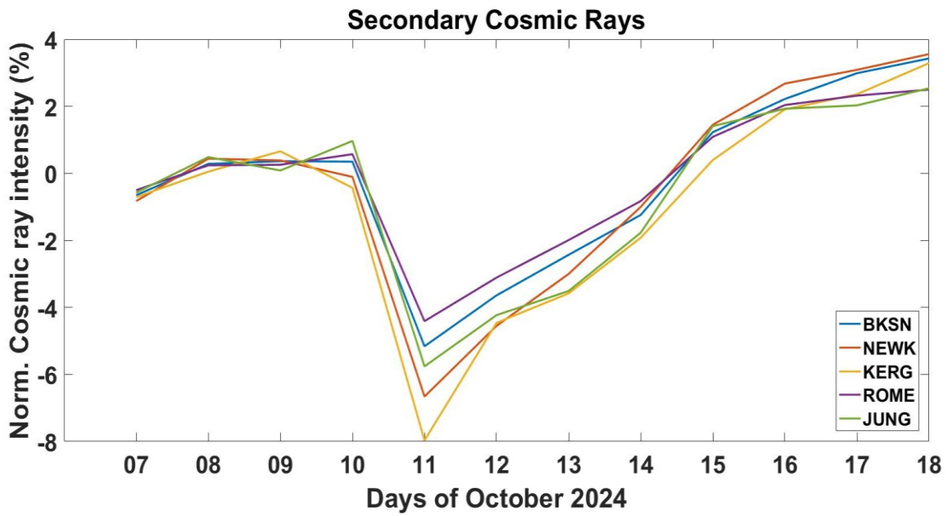


Fig.1: The normalized CR intensity for middle latitude stations obtained from NMDB.

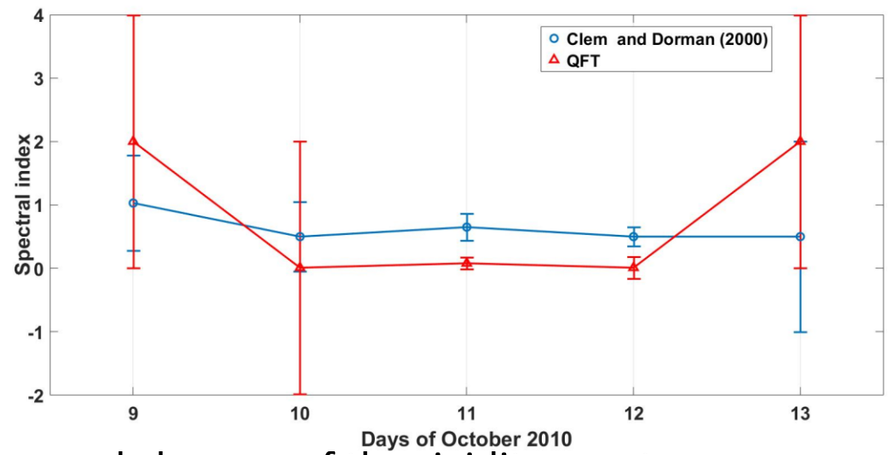


Fig.2: Temporal changes of the rigidity spectrum exponent γ applying the coupling function of Xaplanteris et al. (2021) (red line) and the function of Clem and Dorman (2000) (blue line).

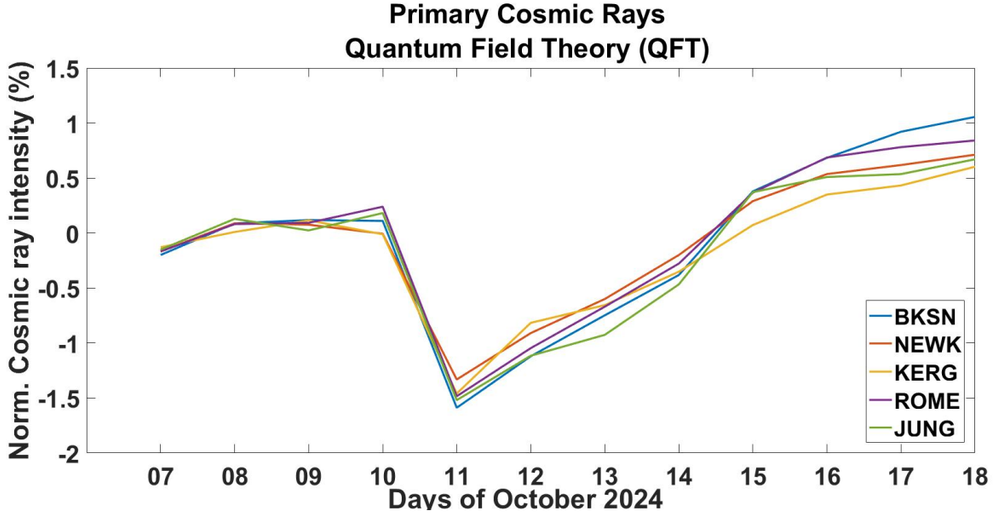


Fig.3: Time profiles of the primary cosmic ray variations applying the coupling function of Xaplanteris et al. (2021).

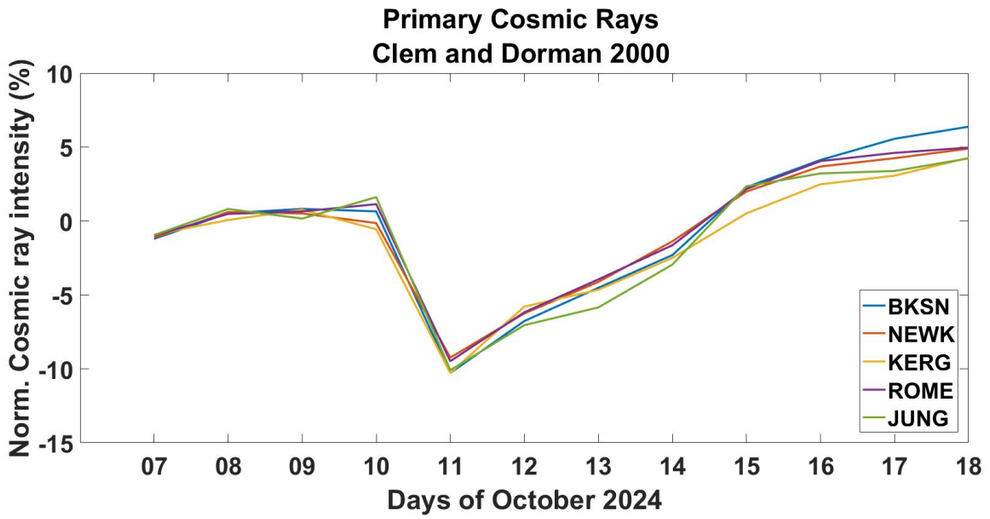


Fig.4: Time profiles of the primary cosmic ray variations applying the coupling function of Clem and Dorman (2000).

3. Results

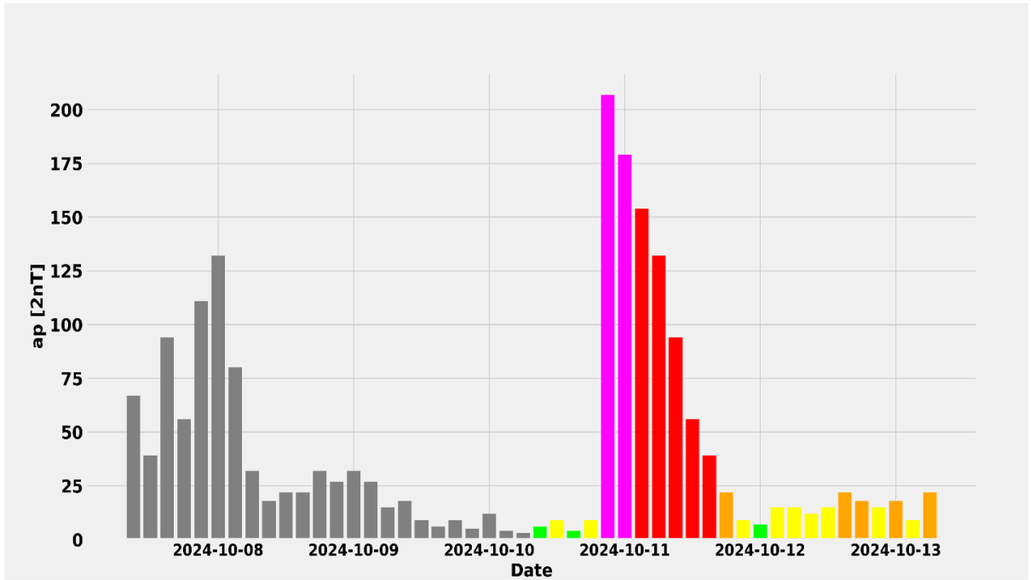


Fig. 5: Coloured scaled plot of ap values showing in grey colour past 72 hours from October 07, 2024 to October 10, 2024 (actual data provided by GFZ) and the forecasted values for the next 72 hours from October 10, 2024 to October 13, 2024. (*https://swe.ssa.esa.int/ap_Prediction-federated*)

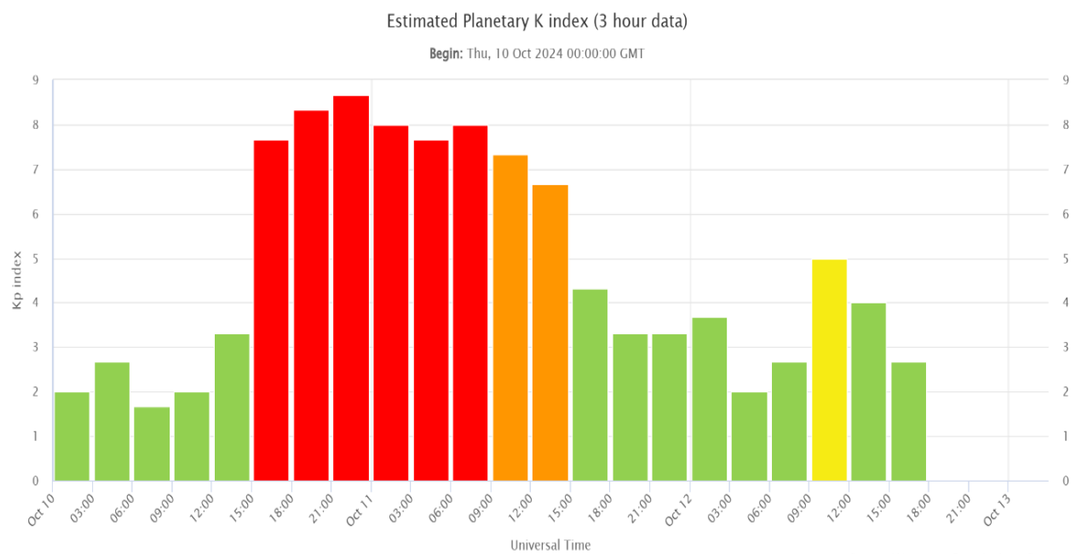


Fig. 6: The Kp index values during the geomagnetic storm of October 10-11. (http://www.swpc.noaa.gov/products/planetary-k-index)

- The expected ap max value calculated 207 ($k_p=8^0$) on October 10, 2024 at 21:00 UT by the tool. However, the actual ap index reached its max value of 300 ($k_p=9^-$) on October 10, 2024 at 21:00 UT, as reported by GFZ (http://www-app3.gfz-potsdam.de/kp_index/qlyymm.html).

- **The automated ap tool predicted successfully the geomagnetic storm of October 10-11, 2024.**

4. Conclusions

- The results of the geomagnetic storm were spotted on the cosmic ray intensity, a Forbush decrease started on October, 10 2024 as a result of the arrival of CME.
- Following the method of Alania and Wawrzynczak (2012) the calculated cosmic ray intensity in the heliosphere by these two coupling functions is almost the same for all stations in the case of the selected Fd of October 2024.
- The calculated spectral index follows well the cosmic ray intensity during the Fds (*Livada and Mavromichalaki, 2020).* The spectral index decreases in the minimum and near minimum phases of the Fd in both cases of coupling functions.
- The ap tool predicted with high accuracy the arrival time of the CME and the level of geomagnetic storm. The maximum value of the predicted apmax was 207 nT on October, 10 2024 at 21:00 UT, while the actual value of apmax (according to GFZ) was 300 nT on October, 10 2024 at 21:00 UT.

5. References

- Alania, M., Wawrzynczak, A.: Energy dependence of the rigidity spectrum of Forbush decrease of galactic cosmic ray intensity. Adv. Space Res., 50, 725-730, 2012.

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- Livada, M., Mavromichalaki, H.: Spectral Analysis of Forbush Decreases using a new yield Function, Solar Phys, 295:115, 2020.

- Mavromichalaki, H., Livada, M., Stassinakis, A., Gerontidou, M., Papailiou, M.-C., Drube, L. and Karmi, A. : 'The ap Prediction Tool Implemented by the A.Ne.Mo.S./ NKUA Group', Atmosphere 2024, 15, 1073.

- Xaplanteris, L., Livada, M., Mavromichalaki, H., Dorman, L., Georgoulis, M.K., Sarris., T. E.,: Improvements in the coupling function between primary and ground level cosmic ray particles based on neutron monitor data, Solar Phys., 296, 91, 2021.

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