Heliospheric modulation of cosmic rays

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Outline

The main character - our Sun

Hale cycle consisting of two successive 11-year SA cycles in GCR

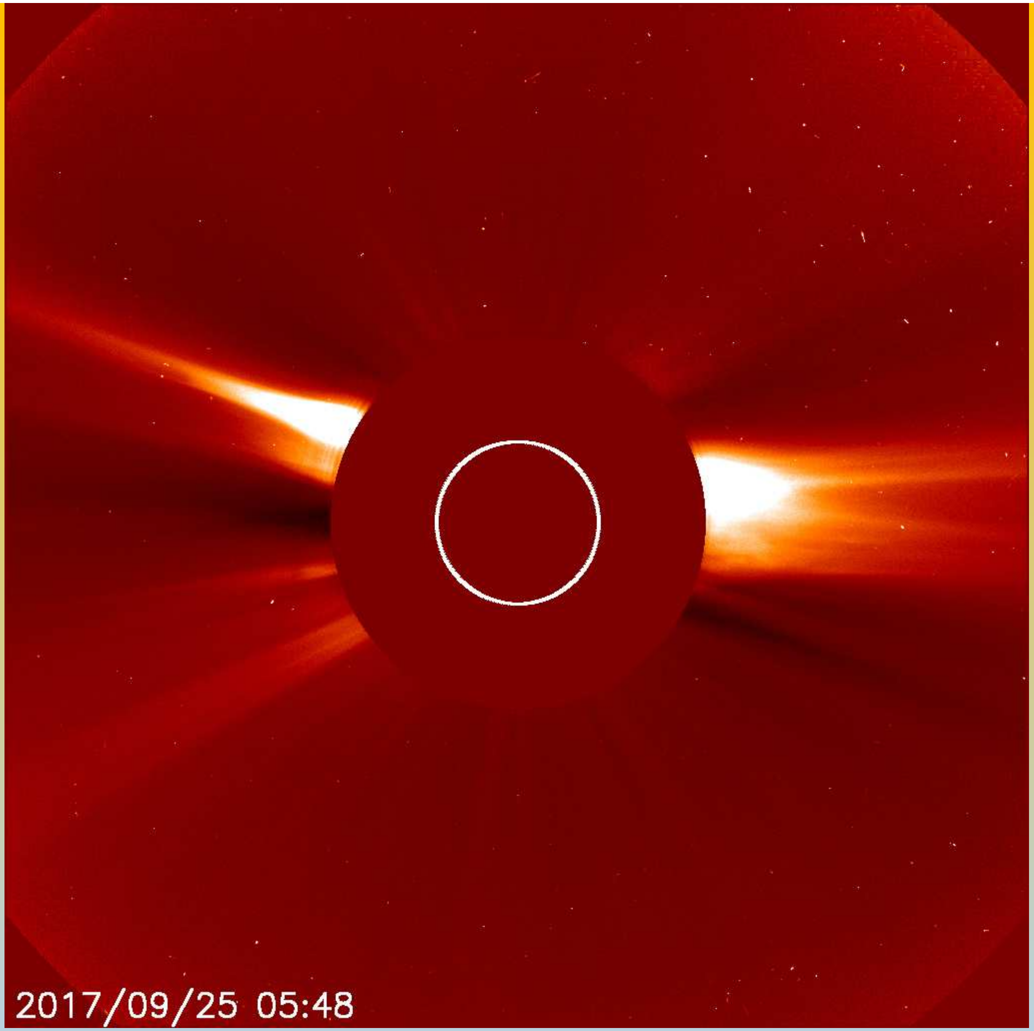
Recurrent galactic cosmic rays intensity variation

3-4 CRP

Forbush decreases

Anisotropy of GCR

GLE



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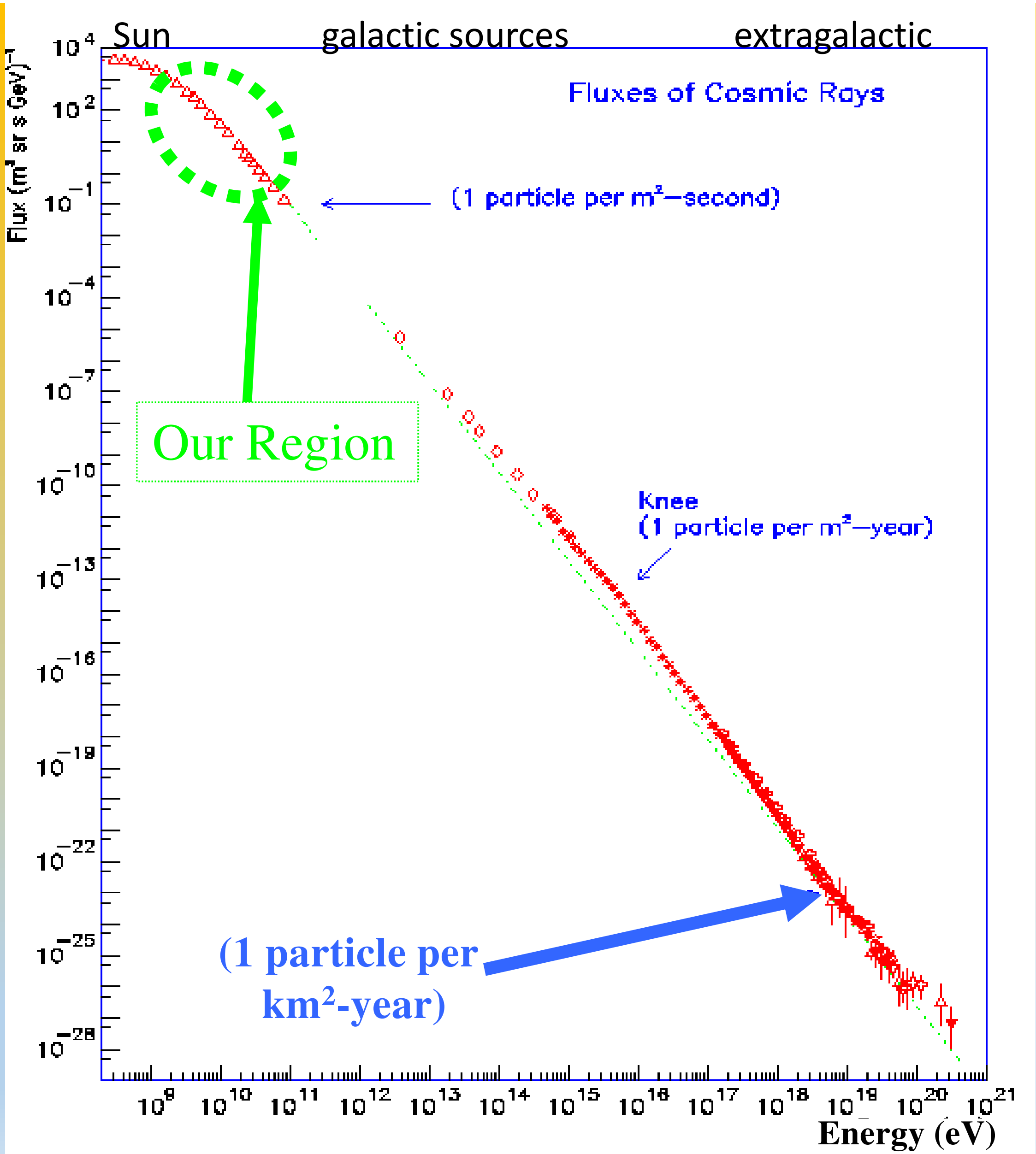
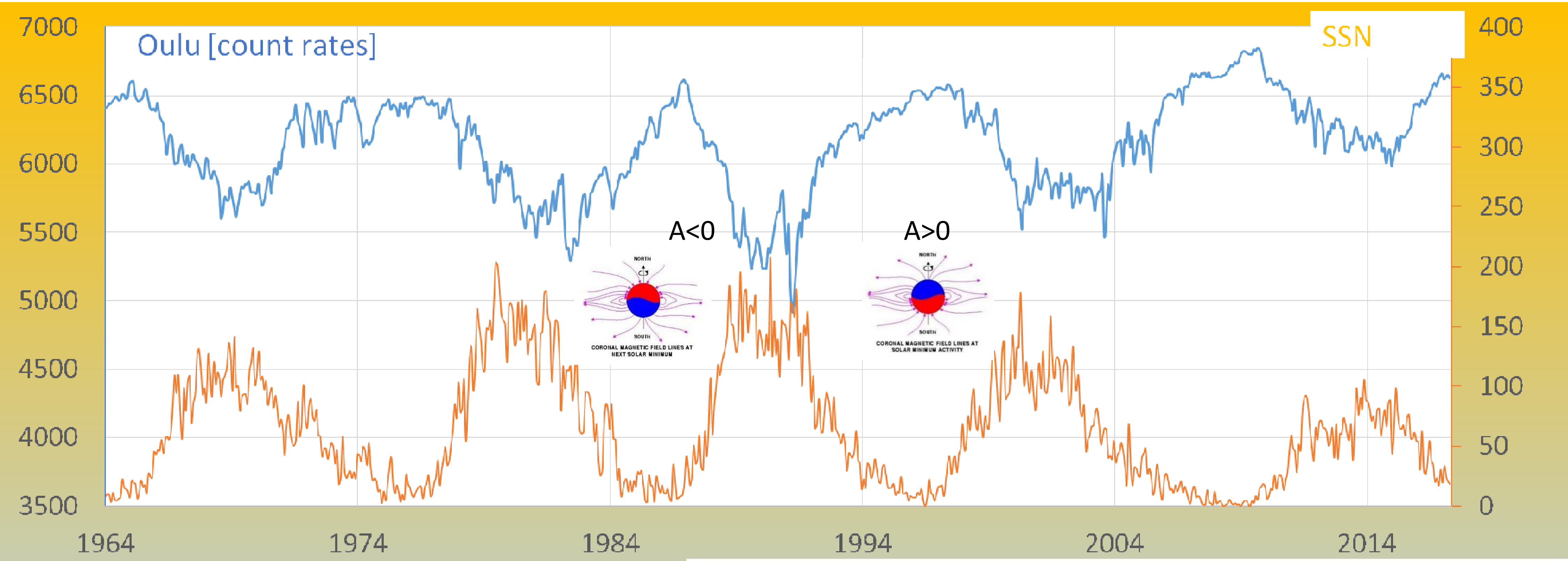
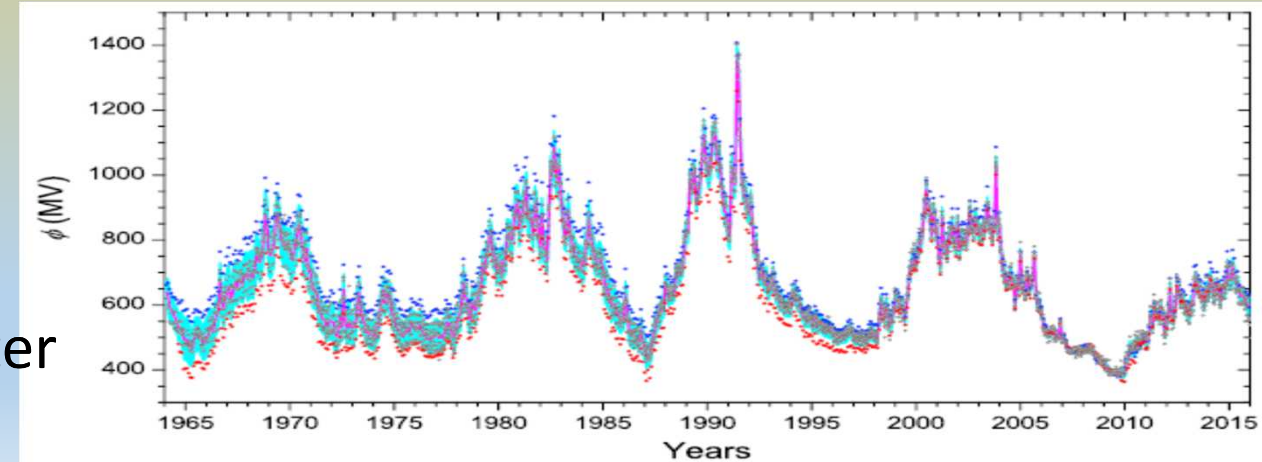


CERN Courier, Jan 29, 1999



27-days averaged data, 1964 -2017, of GCR by Oulu NM and SSN



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Modulation parameter

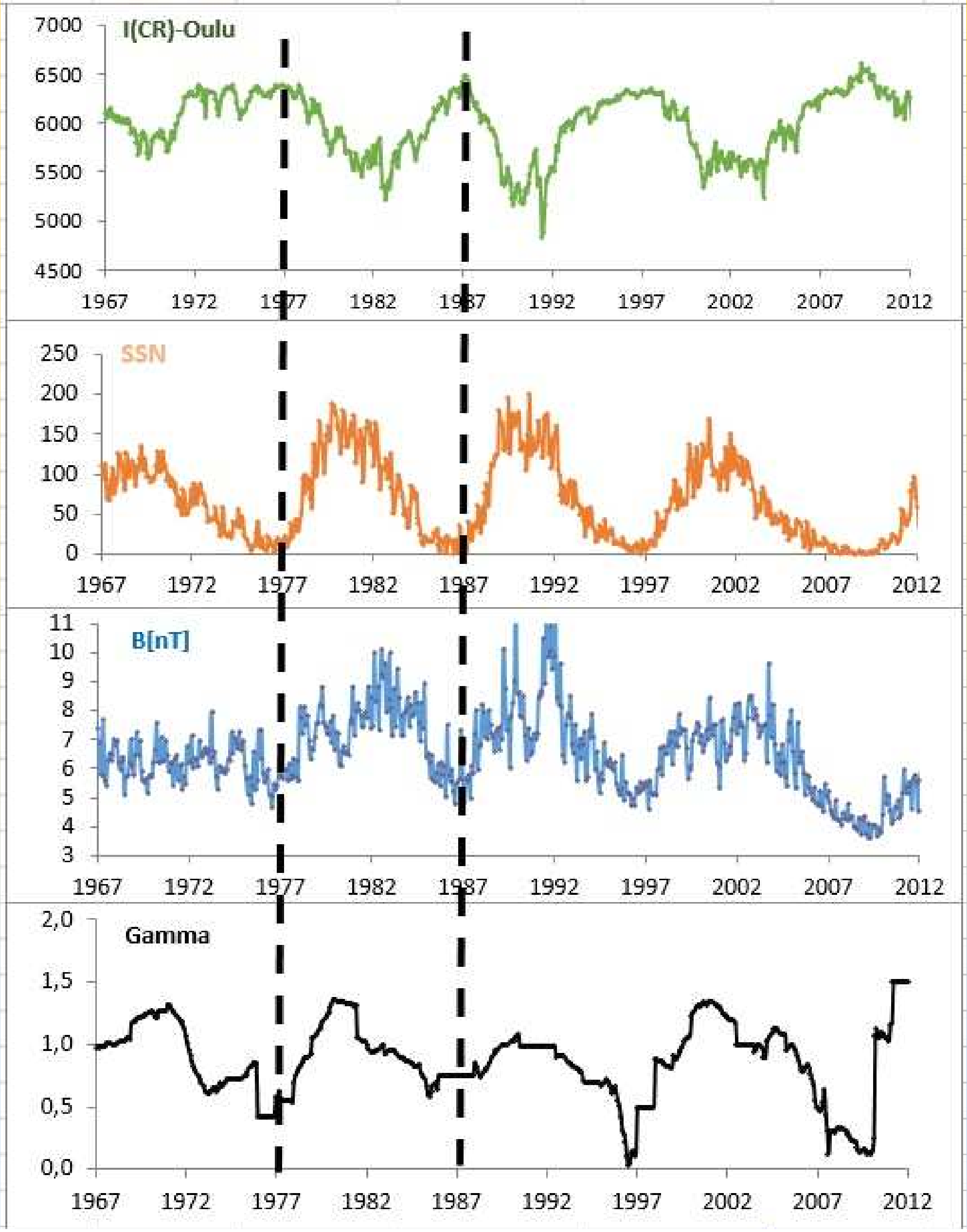
Usoskin, et al., 2017

NMDB stations by Askar Ibragimov, 2008

http://www.nmdb.eu/

The effective energy is found as 11–12 GeV/nuc for the standard polar neutron monitor

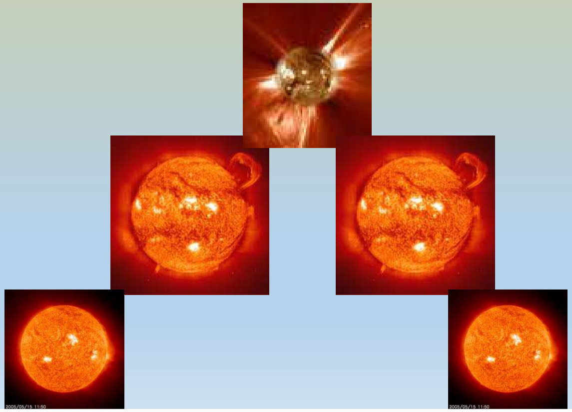
Asvestari, et al., 2017



e.g. 1976-1987

- Temporal changes of the GCR intensity observed by Oulu NM
- Monthly smoothed SSN
- The strength B of the HMF
- Rigidity exponent gamma of the GCR intensity variation

Siluszyk et al., 2015



*Power Spectral Density (**PSD**) of the HMF's turbulence*

$\boxed{\nu}$

$$PSD \propto f^{-\nu}$$

$$\alpha = 2 - \nu$$

$$\nu = -1.04\,\gamma + 2.06$$

The rigidity spectrum exponent the isotropic intensity variations of GCR

$\boxed{\alpha}$

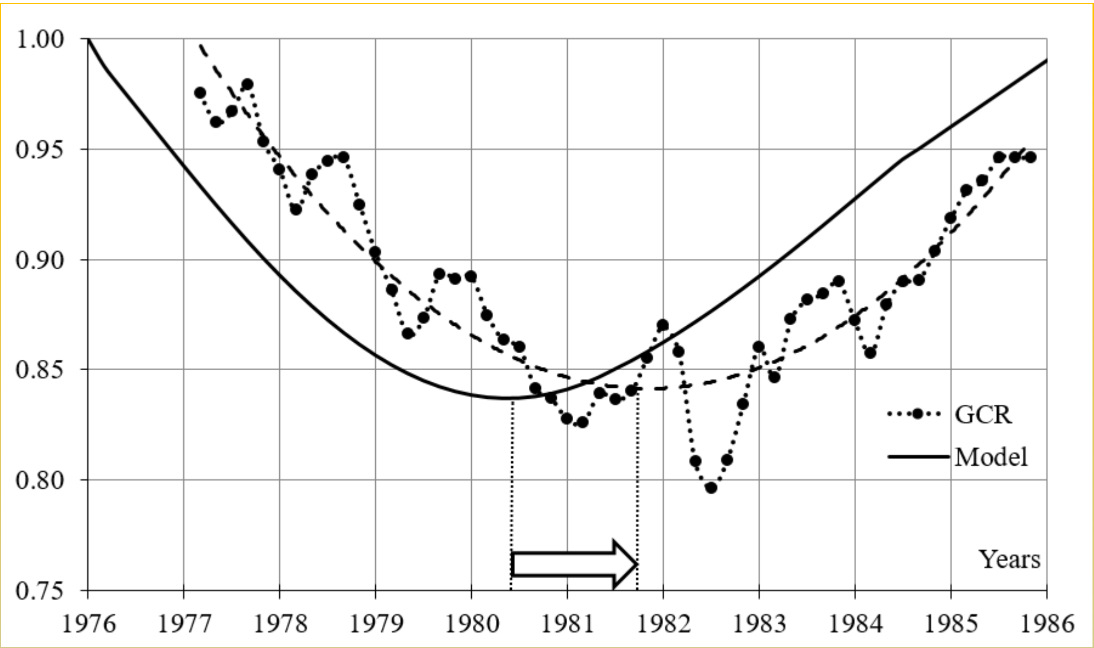
$$\gamma(\alpha) = 0.96 \cdot \alpha + 0.06$$

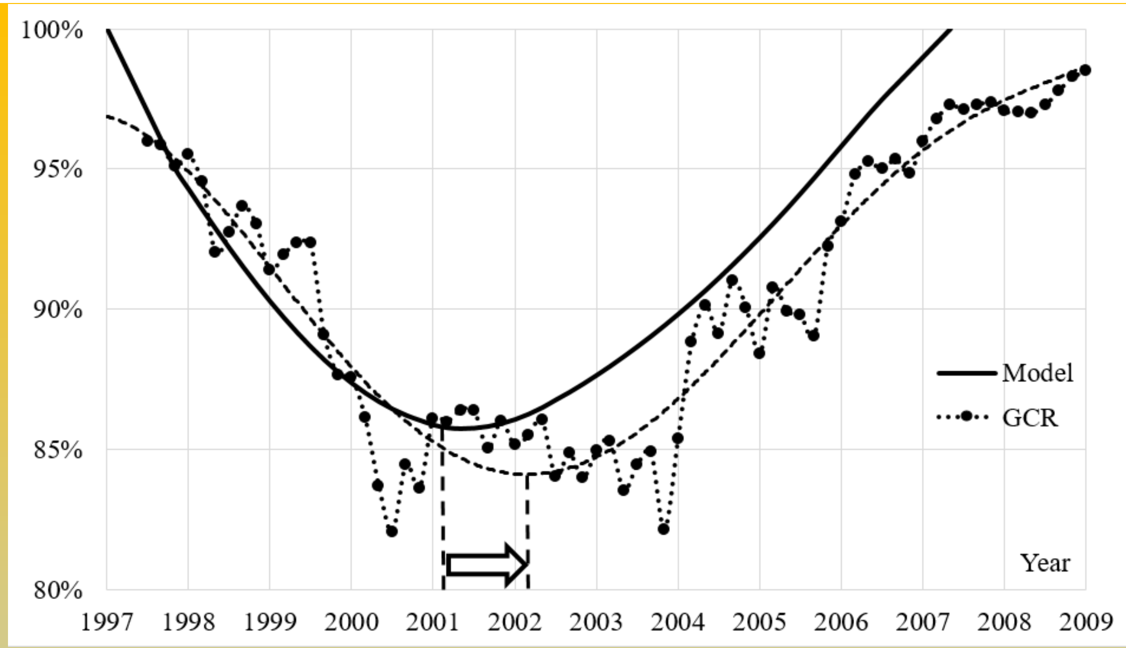
$\boxed{\gamma}$

Diffusion

$$A \propto \frac{1}{K_{\parallel}} \propto \frac{1}{R^{\alpha}}$$

$$\frac{\delta D(R)}{D(R)} \propto \frac{1}{R^{\gamma}}$$

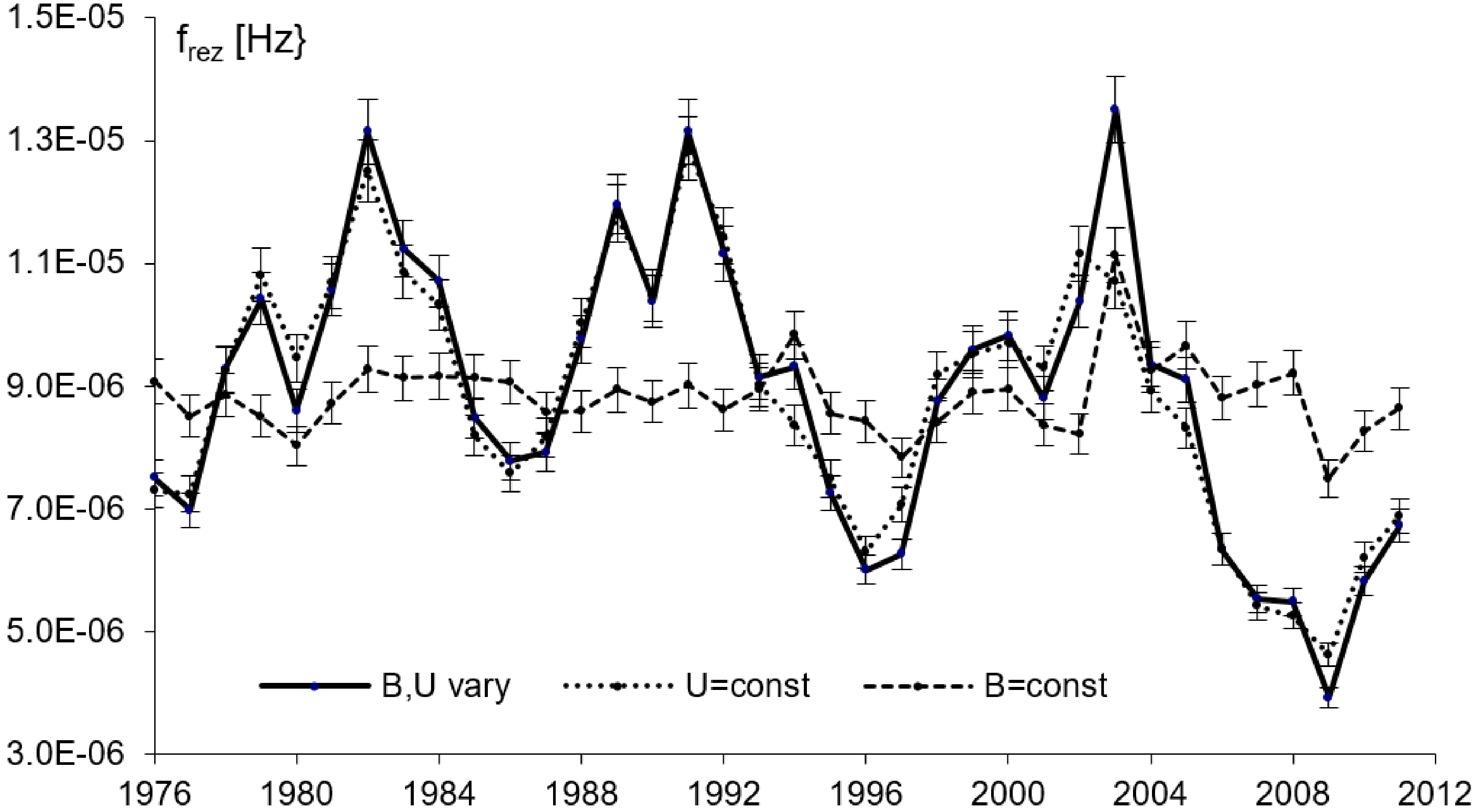




Temporal changes of the amplitude of the long period variation and approximated observed changes of the GCR intensity (dotted line). Model – the solution of the PDE for the rigidity of 10 GV (solid line) in period 1976 –1986.

Temporal changes of the amplitude of the long period variation and approximated observed changes of the GCR intensity (dotted line). Model – the solution of the PDE for the rigidity of 10 GV (solid line) in period 1997 –2009.

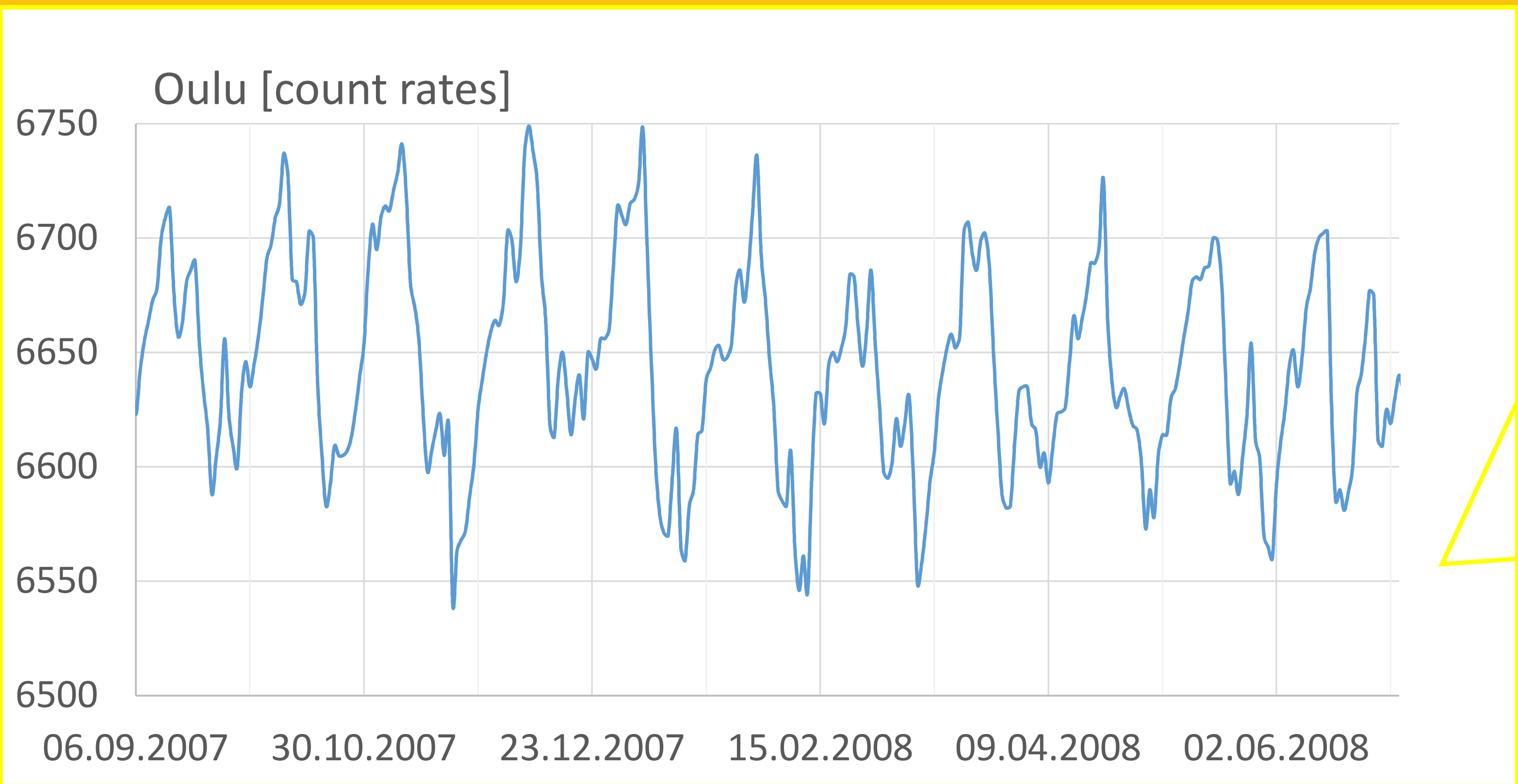
Siluszyk et al., 2017; Siluszyk et al., 2011

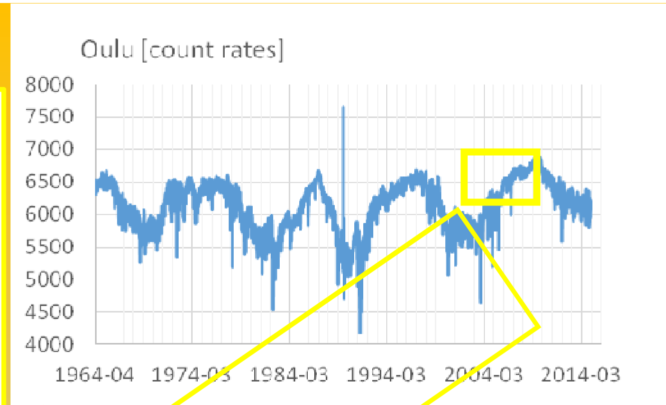


$$f_{res} = \frac{300}{2\pi} \frac{U_{SW} \cdot B}{R}$$

Yearly alternations of the resonant frequency for rigidities 10 GV of GCR protons in 1976 - 2011; (a) the solid line – B and U_{sw} changeable, (b) the dotted line – B changeable and U_{sw} is constant, and (c) the dash line – U_{sw} changeable and B is constant with the cycle of SA.

Siluszyk et al., 2015





Daily data, 2007 -2008, of the GCRs by Oulu NM

(cosmicrays.oulu.fi)

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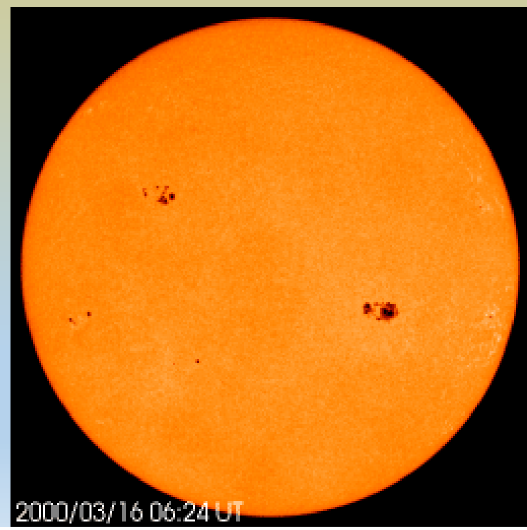
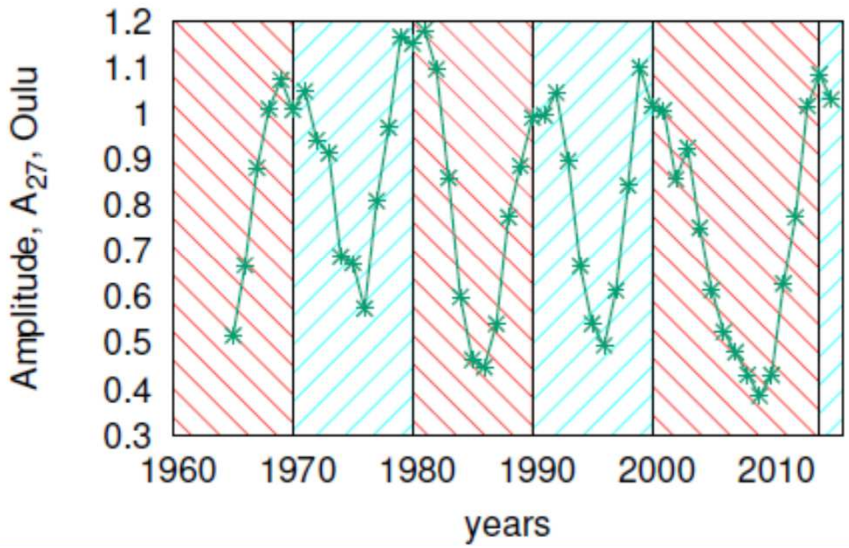
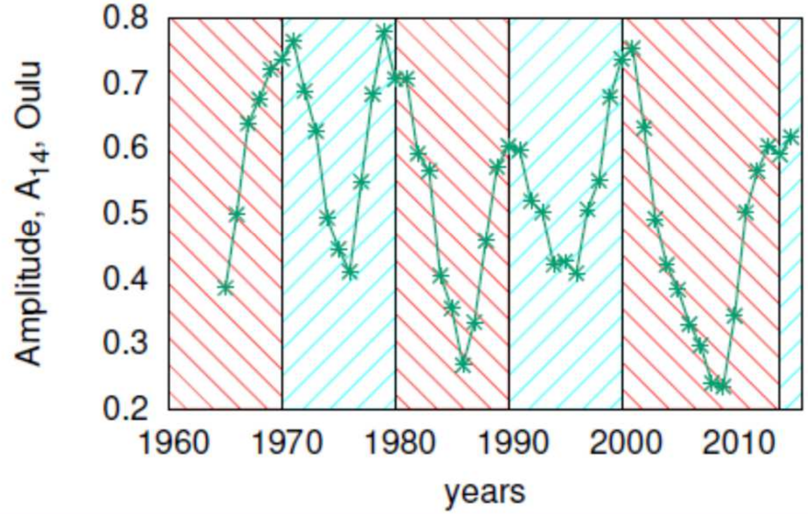
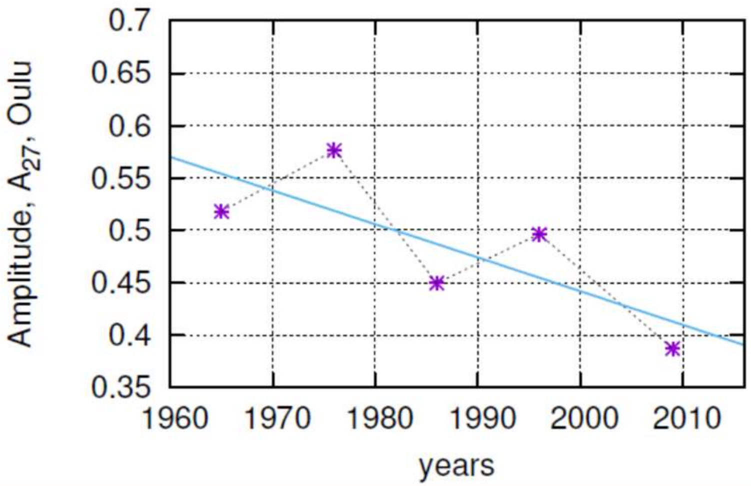


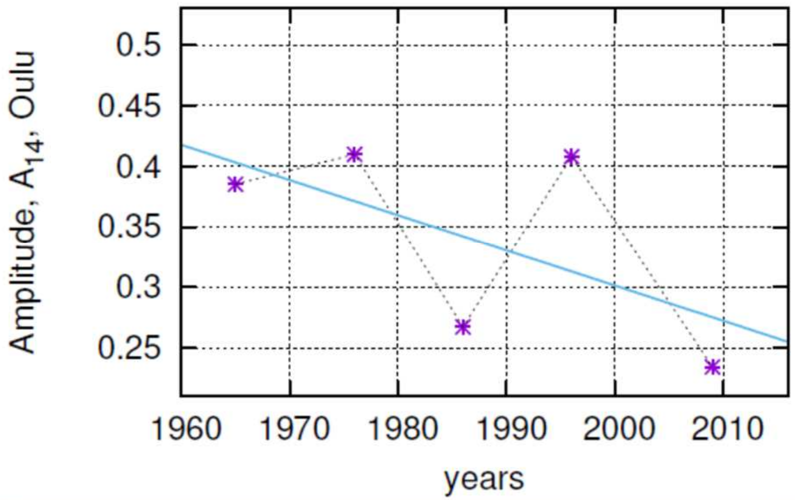
http://www.astro.washington.edu





3-year running means of yearly averaged amplitudes of the 1st and the 2nd harmonics of GCR for Oulu NM





3-year means of amplitude of the 1st and the 2nd harmonics for the last five solar minima with linear trend

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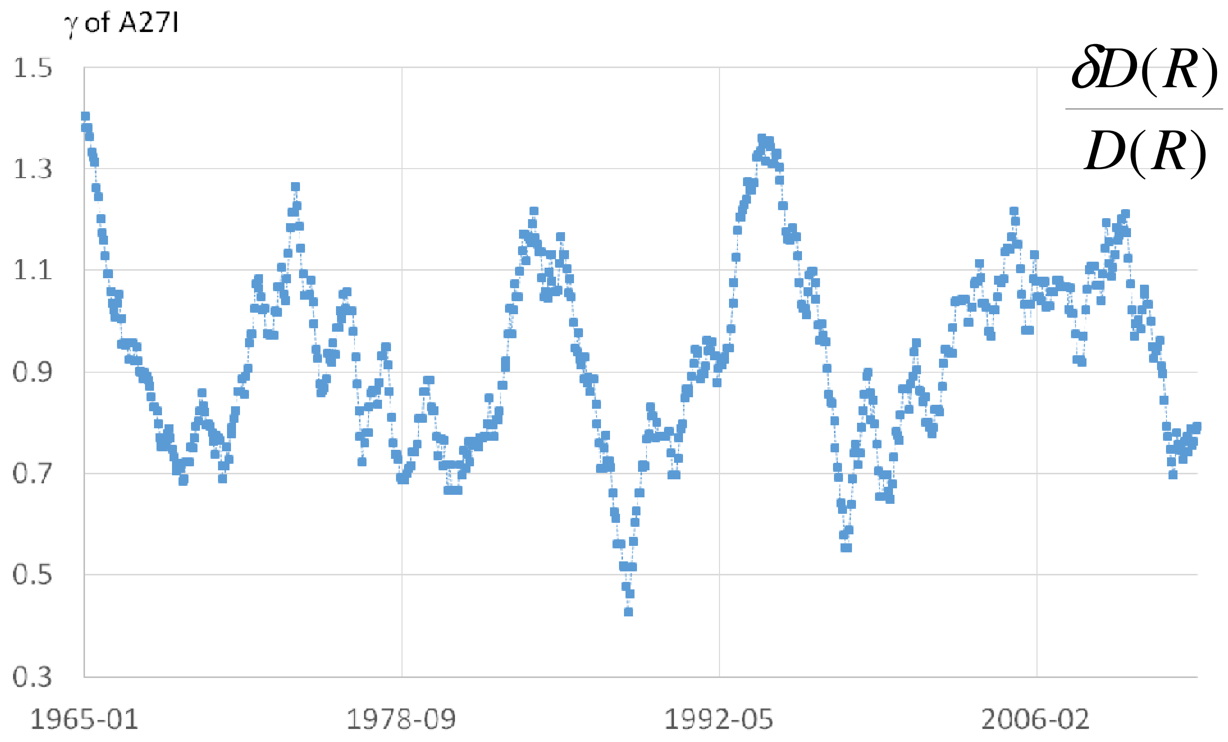
Gil, Mursula, 2017



$$\frac{\delta D(R)}{D(R)} = \begin{cases} A R^{-\gamma} \; for \quad R \le R_{\max} \\ 0 \quad for \quad R > R_{\max} \end{cases}$$

Dorman, 1963; Ahluwalia, Ericksen, 1971; Yasue et al., 1982

The changes of the rigidity spectra exponent γ of the 27-days variation of the GCR intensity calculated using Kiel and Rome neutron monitors in 1965-2014 (smoothed over 39 Carrington rotations).

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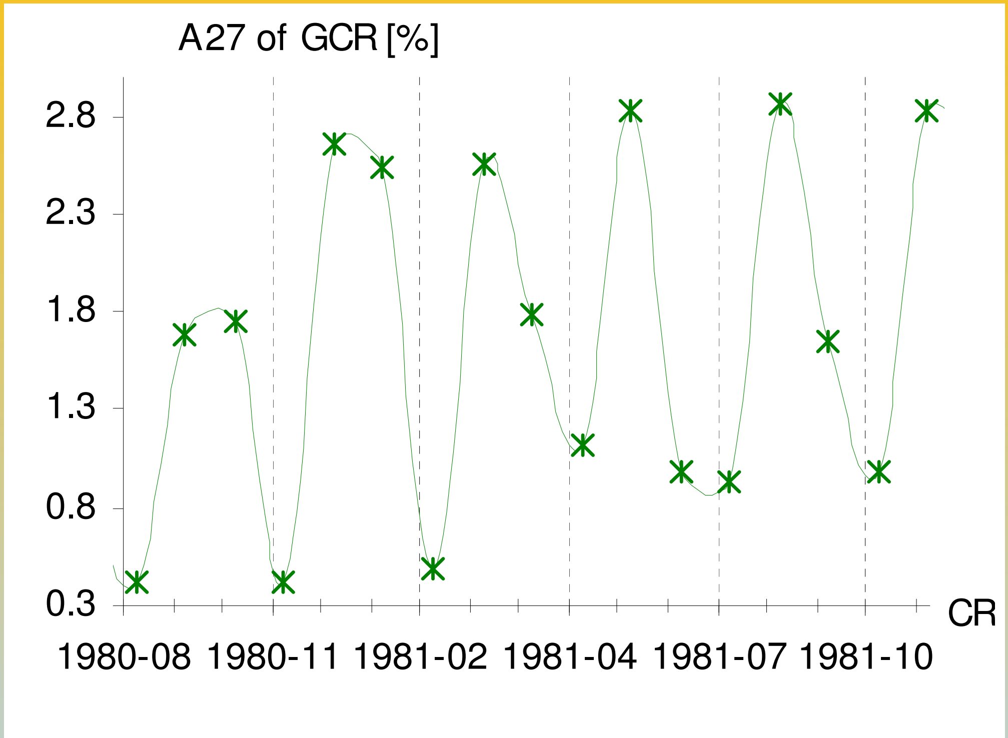
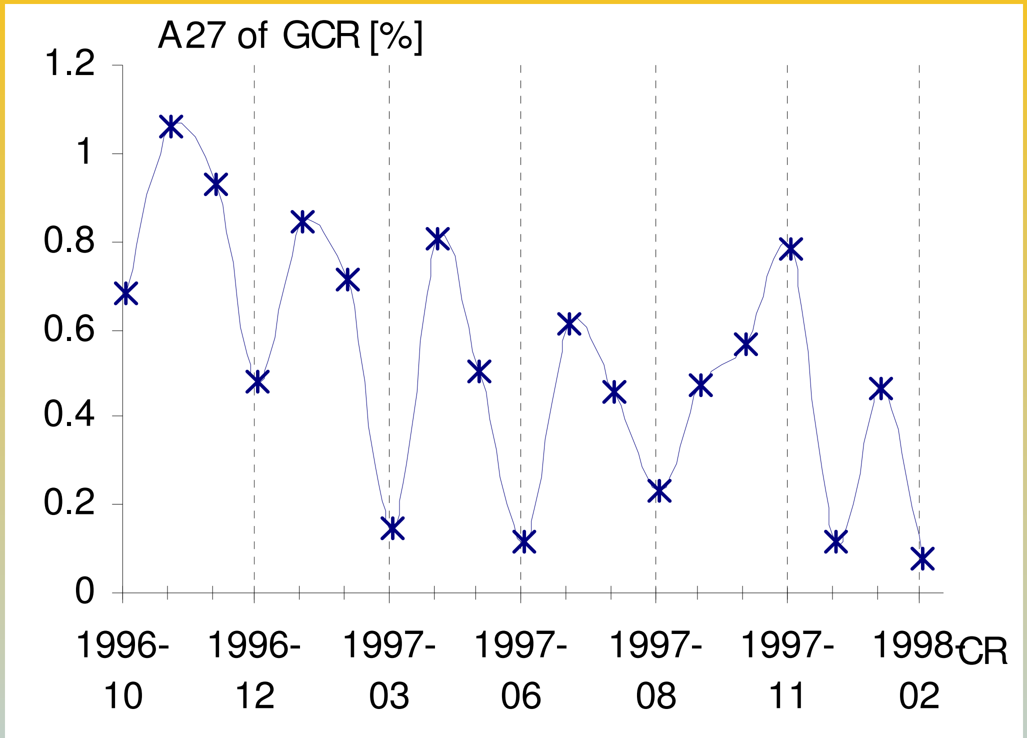
Gil, Alania, 2016

The 3-4 CRP **quasi-recurrence**



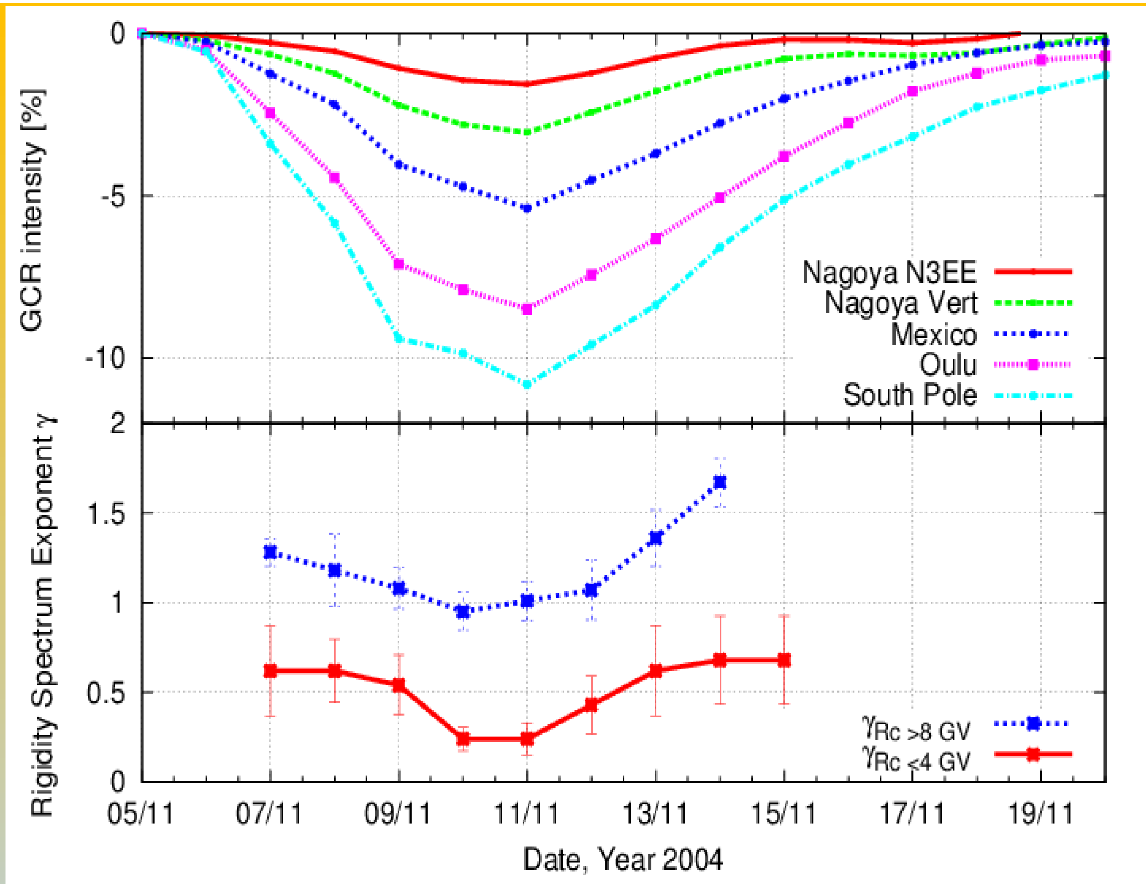


Sequences of the 3-4 CRP (three to four Carrington rotations period) in 1980-1982 (maximum epoch of SA) and in 1996-1998 (minimum of SA) of amplitudes of the 27- day variation of the GCR intensity by Kiel NM

Gil, Alania, 2011; 2012

November 5-19, 2004

Smoothed over 3 days temporal changes of the GCR intensity for the NMs and Nagoya muon telescope channels during Fd. Temporal changes of the rigidity spectrum exponent based on the data of the stations divided in two groups according to their cut off rigidities for **low Rc<4 GV**, and **high Rc>8 GV** cut off rigidities



Rc>8 GV Hale, Mexi, N0VV, N1EE, N3EE, N4NE, N4SE

Rc<4 GV Calg, Caps, Kerg, McMu, Oulu, Sopo

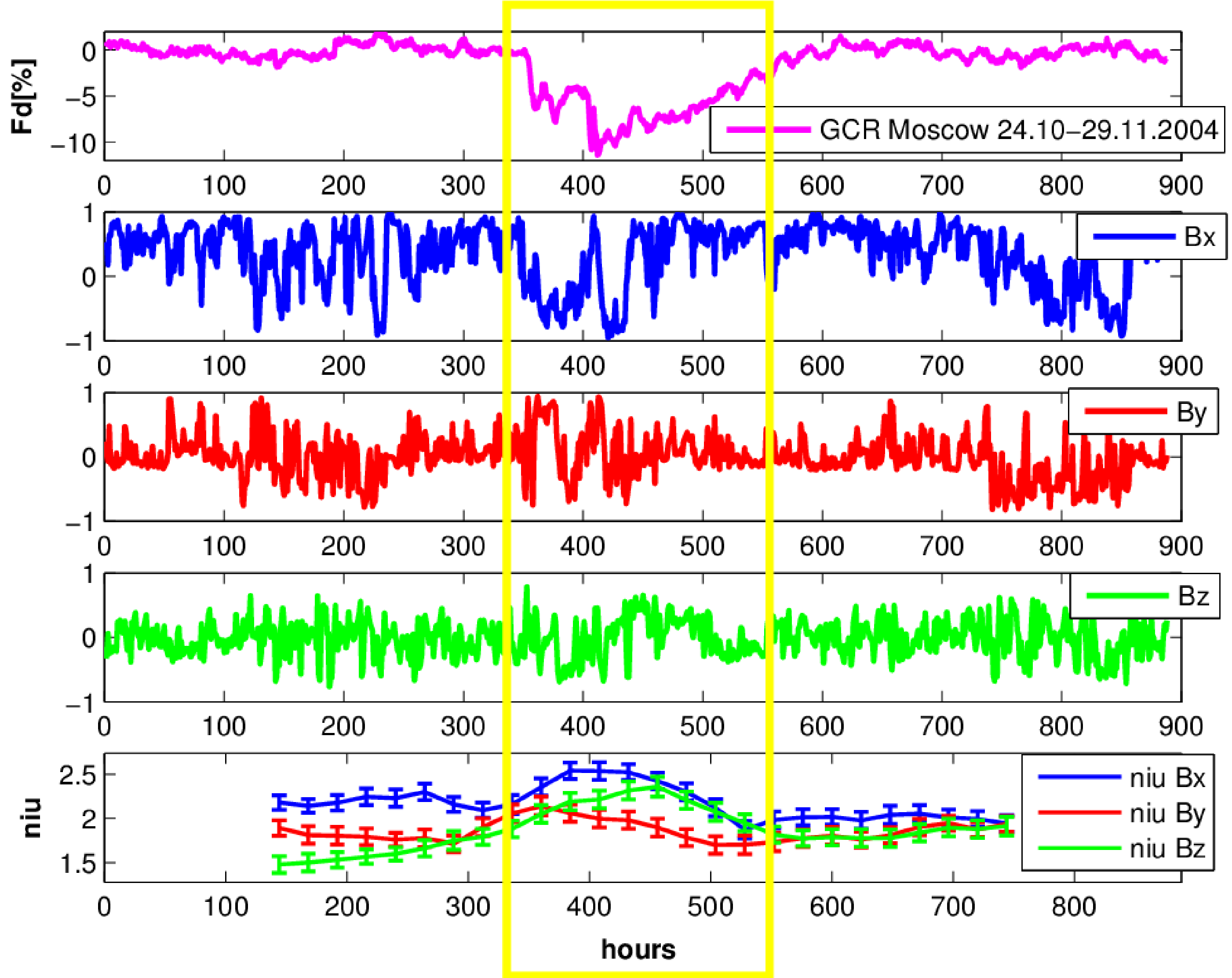
(Wawrzynczak&Alania 2015 J. Phys.: Conf. Ser.632 012083)

Background

- We have showed (e.g. Wawrzynczak and Alania 2005, 2008, 2010) that the changes of the rigidity R spectrum
  $\boldsymbol{\delta D(R)/D(R) \propto R^{-\gamma}}$
  of the Fds determined by NMs and ground MT data, are related with the changes of the PSD of the IMF's turbulence
  (**PSD** $\propto$ **f** $^{-\nu}$, f is a frequency)
- Particularly exists a relationship $\gamma \propto \mathbf{2} - \nu$
- We consider that this relationship exists owing to the dependence of the diffusion coefficient K of GCR particles on the rigidity R according to the quasi linear theory (QLT)

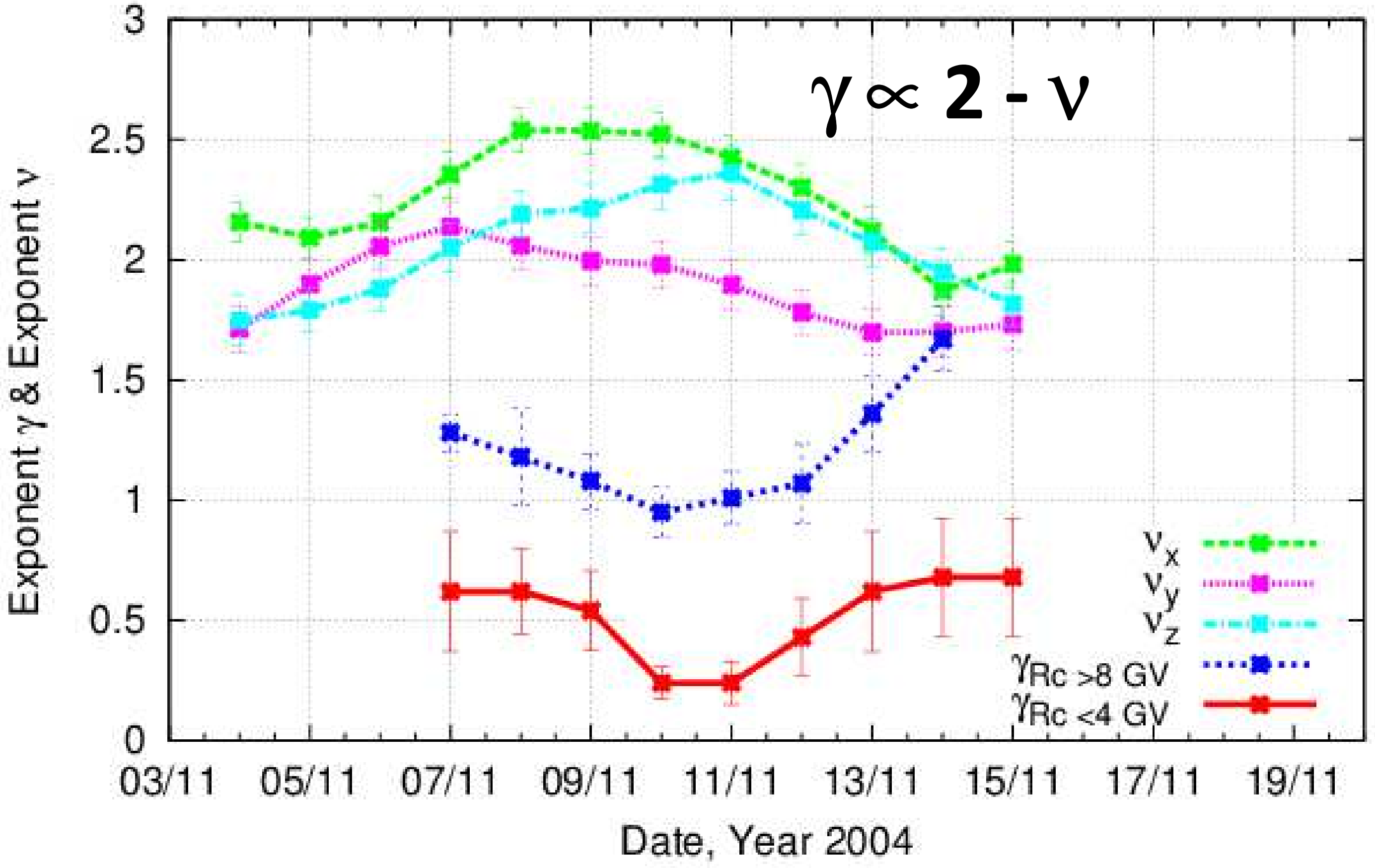
$$K \propto R^{2-\nu},$$

[Jokipii, 1966; Hasselman and Jokipii, 1971, Toptygin, 1985] *Wibberentz , 1968*



Running PSD, November 2004

The values of the exponent ν of the PSD for HMF components based on the 12 days running series of hourly data in October, 24 –November, 29, 2004 (Wawrzynczak&Alania 2015 J. Phys.: Conf. Ser.632 012083)



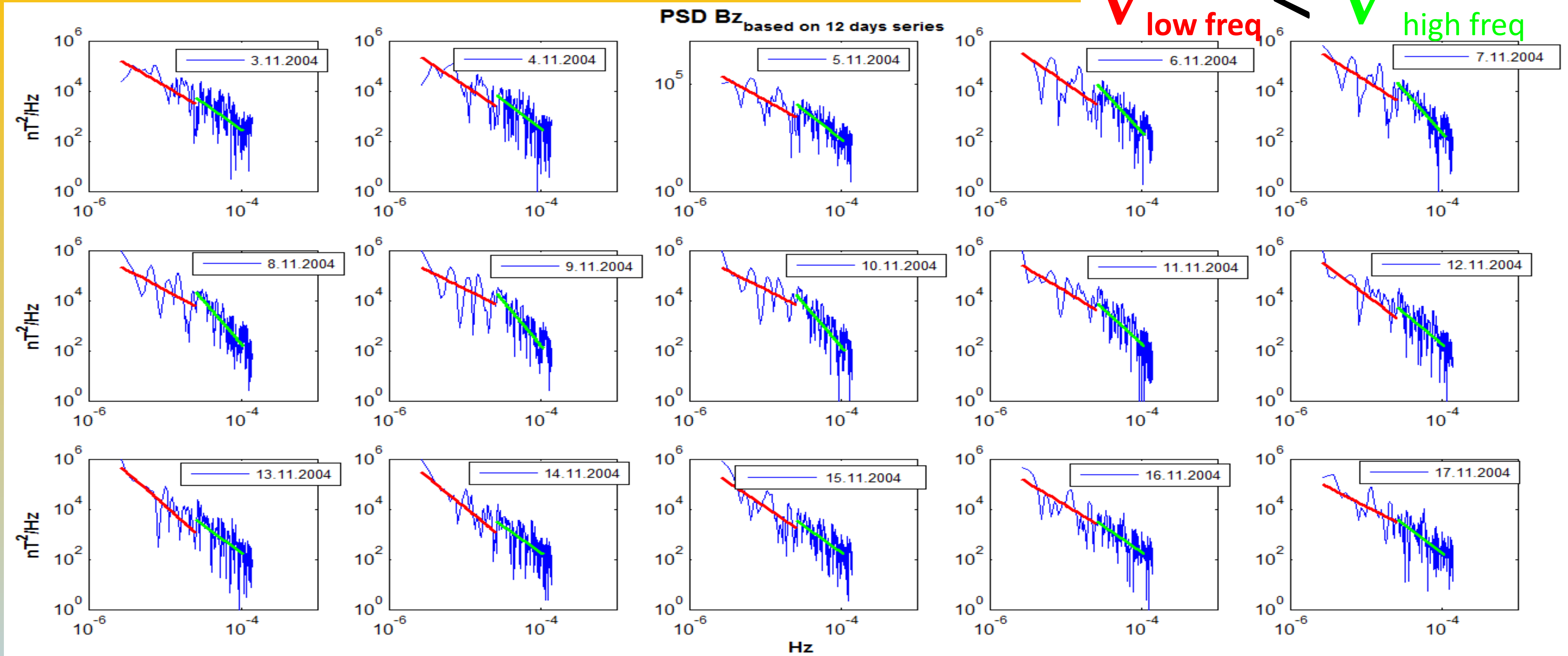
November 5-20, 2004

Temporal changes of the exponent γ and ν during Fd in November 3-10, 2004 (Wawrzynczak&Alania 2015 J. Phys.: Conf. Ser.632 012083)

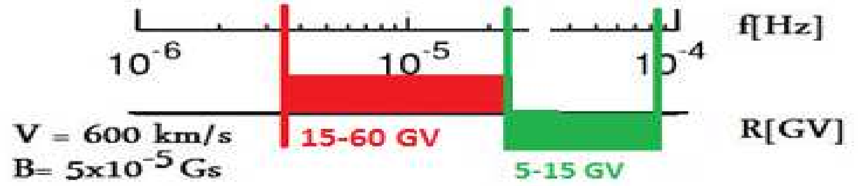
Correlation Coefficient	**ν_Bx**	**ν_By**	**ν_Bz**
$\gamma_{Rc>8\ GV}$	**-0.88±0.02**	**-0.46±0.23**	**-0.94±0.01**
$\gamma_{Rc<4\ GV}$	**-0.57±0.16**	**-0.21±0.32**	**-0.85±0.03**

PSD Bz, November 3-17, 2004

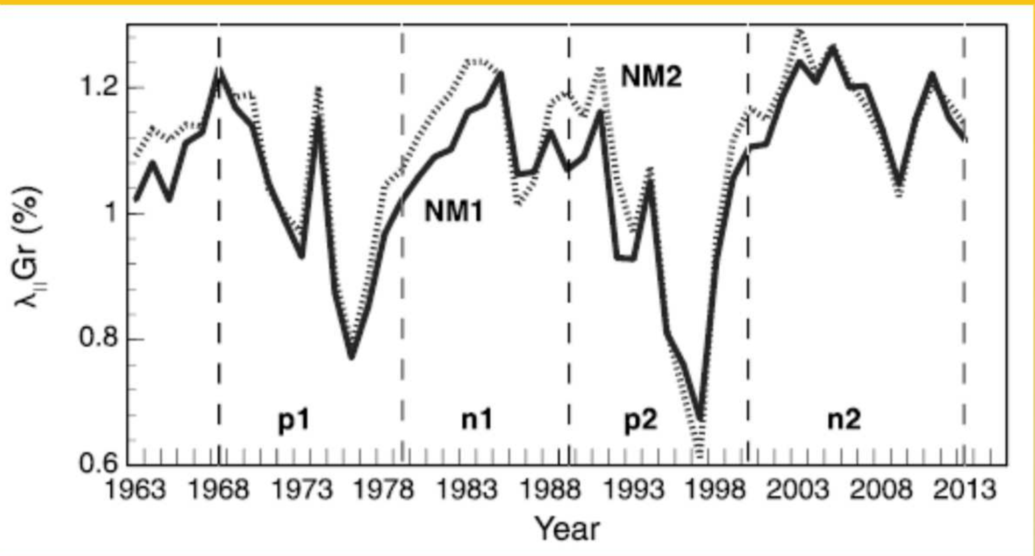
$\nu_{\text{low freq}} < \nu_{\text{high freq}}$



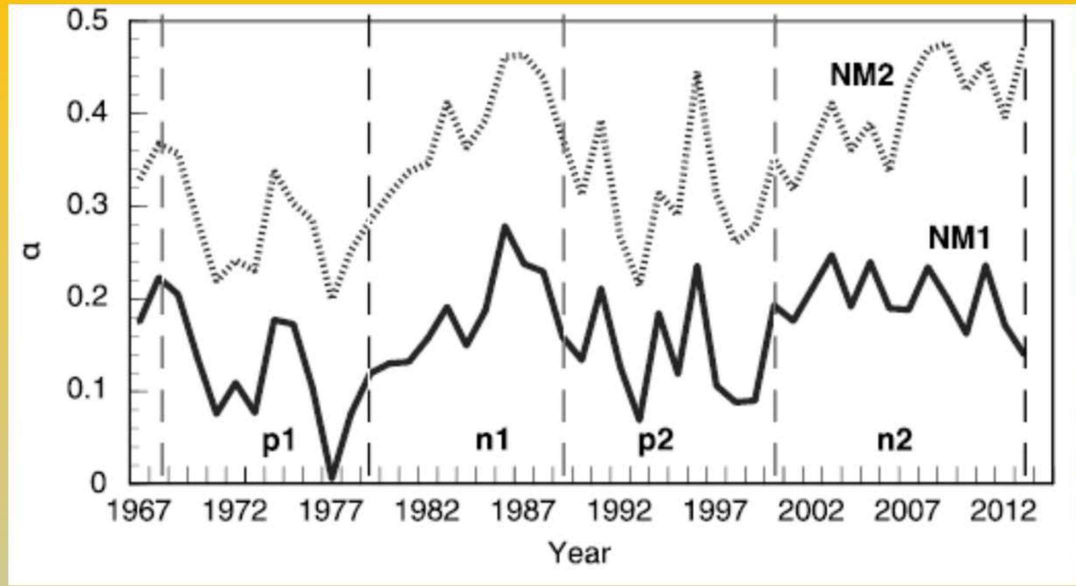
The PSD for IMF component Bz based on the 12 days running series of hourly data in November 2004 (Wawrzynczak&Alania 2015 J. Phys.: Conf. Ser.632 012083)



Ahluwalia, Ygbuhay, Modzelewska, et al., JGR-Space Physics, 2015:



Yearly λ|| Gr (%) for NM1, NM2 in 1963-2013



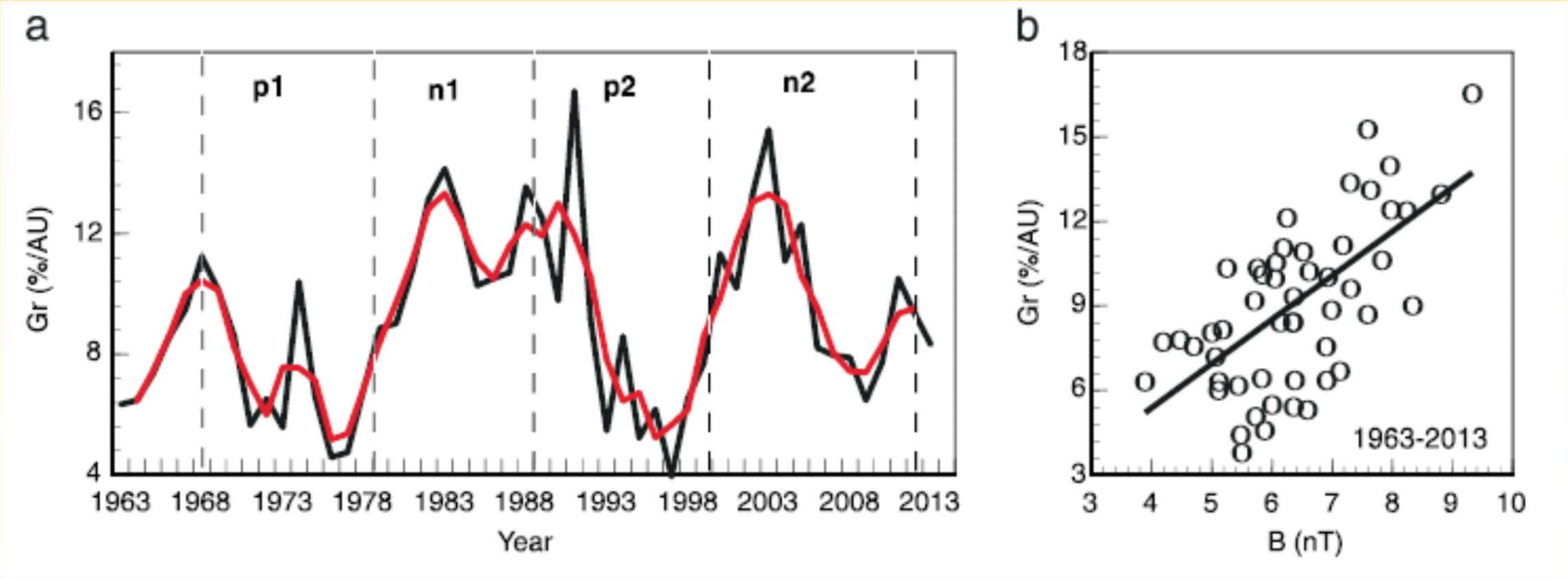
Yearly α for NM1, NM2 in 1963-2013

$$\alpha = \frac{K_\perp}{K_{||}} = \frac{1}{1+(\omega\tau)^2} = \frac{1}{1+\left(\lambda_{||}/r_L\right)^2}$$

$$\lambda_{||}G_r = -A_r + \frac{3CV}{v} + A_\varphi \tan\psi$$

$$\alpha = \frac{\left(\frac{A_r^p+A_r^n}{2} - \frac{3}{v}CV\right)sin2\psi + \left(A_\phi^p + A_\phi^n\right)cos^2\psi}{\left(\frac{A_r^p+A_r^n}{2} - \frac{3}{v}CV\right)sin2\psi - \left(A_\phi^p + A_\phi^n\right)sin^2\psi}$$

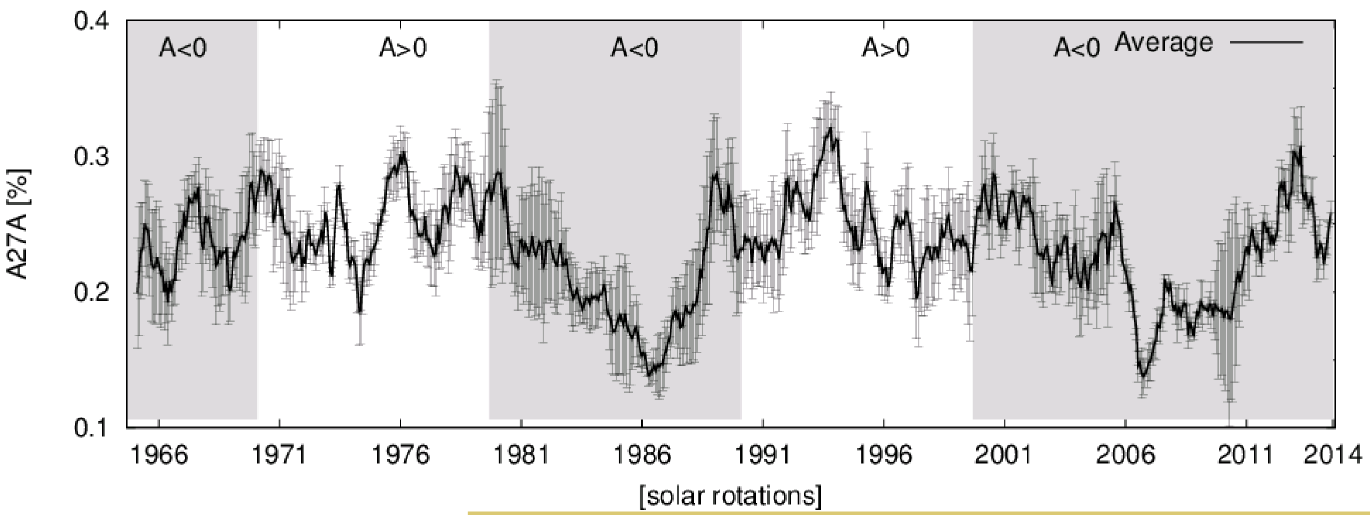
Ahluwalia, Ygbuhay, Modzelewska, et al., JGR-Space Physics, 2015:

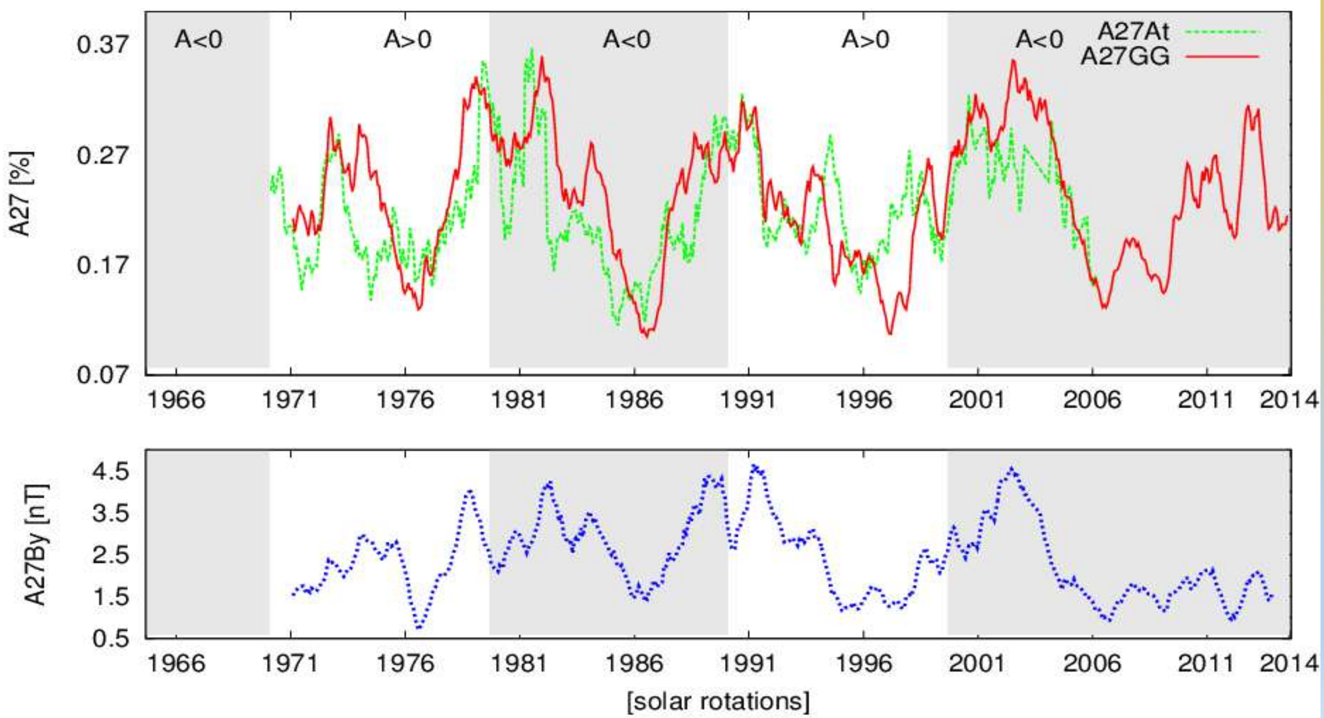


Yearly Gr for NM1, NM2 for 1964-2013 and 3y moving average (red). A scatter plot of Gr (%/AU) versus B (nT)

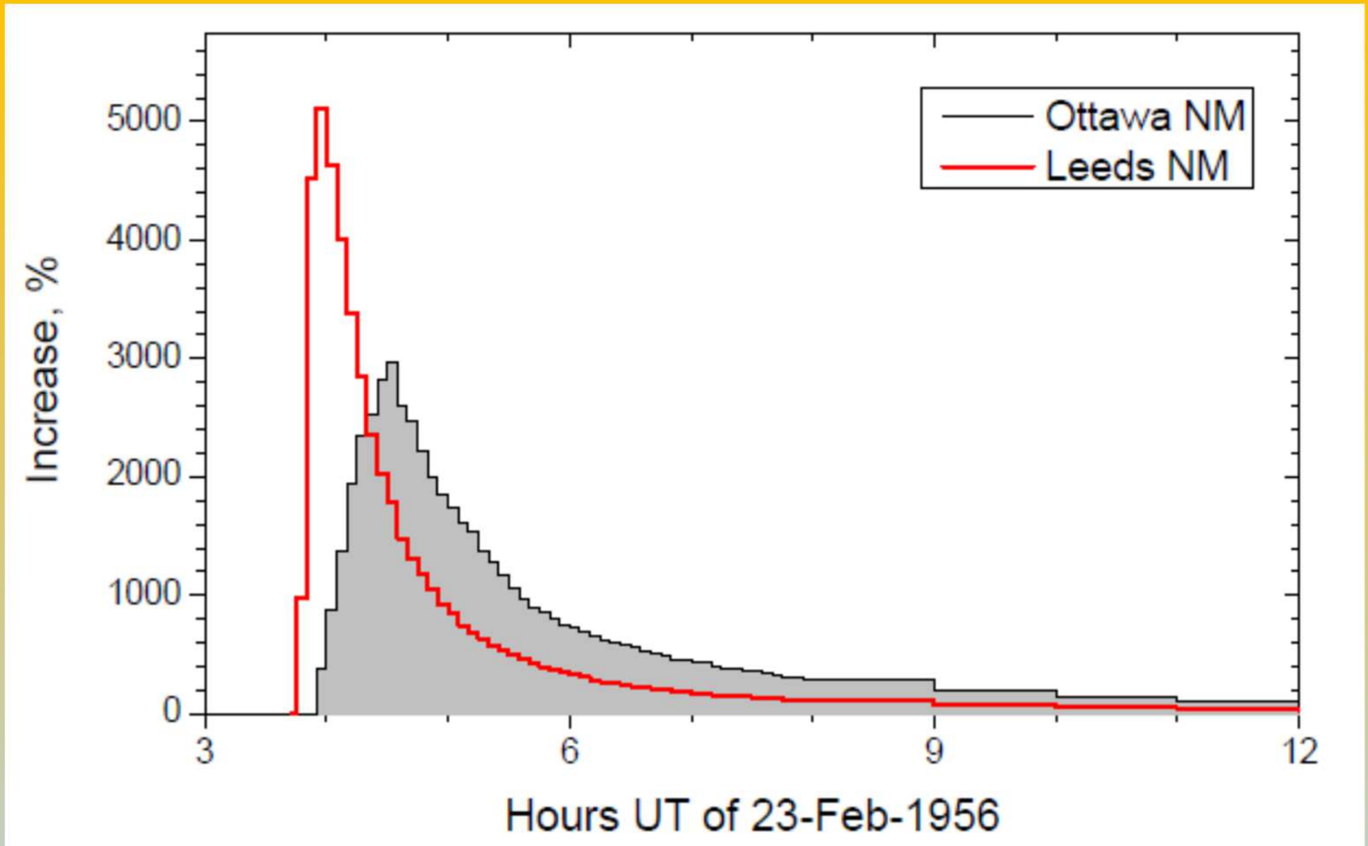
Modzelewska and Alania, AA, 2017, submitted:

Temporal changes of the average A27A smoothed over 13 solar rotations for 6 NMs (Moscow, Kiel, Oulu, Deep River, Climax) in 1965-2014 during A>0 and A<0





Temporal changes of the amplitudes of the 27-day variation of the GG index and At component of the 3D anisotropy (top) and By component of the HMF (bottom) smoothed over 13 Sun's rotations during A>0 and A<0 polarity epochs.



Increase measured by Leeds and Ottawa NMs, during the GLE 5. Leeds NM registered the highest peak increase (5116 %), Ottawa NM detected the most intense integral response (5300 %*hr).

The strong GLE events (the strength I > 100 %*hr) are characterized by a hard spectrum

Asvestari, et al., 2017

Krymsky, 1964; Parker, 1965

$$\nabla\left(\kappa^{s}\nabla f\right)-\left(U+v_{dr}\right)\nabla f+\frac{1}{3}\nabla U p\frac{\partial f}{\partial p}=\frac{\partial f}{\partial t}$$

$$K_{ij}=\begin{pmatrix}\kappa_{11} & \kappa_{12} & \kappa_{13}\\ \kappa_{21} & \kappa_{22} & \kappa_{23}\\ \kappa_{31} & \kappa_{32} & \kappa_{33}\end{pmatrix}$$

$$\psi=arctg\frac{-B_{\varphi}}{B_{r}}=arctg\frac{\Omega r\sin\theta}{U}$$

$$\delta=arctg\frac{B_{\theta}}{B_{r}}$$

$$K_{ij}=K_{ij}^{(S)}+K_{ij}^{(A)}$$

$$\beta=\frac{\kappa_{\perp}}{\kappa_{\|}},\ \beta_{1}=\frac{\kappa_{d}}{\kappa_{\|}}$$

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$$v_{d,i}=\frac{\partial K_{ij}^{(A)}}{\partial x_{j}}$$

Jokipii, Levy and Hubbard, 1977

Tensor

$$\kappa_{11} = \kappa_{\parallel}\left[\cos^2\delta\cos^2\psi + \beta\left(\cos^2\delta\sin^2\psi + \sin^2\delta\right)\right]$$

$$\kappa_{12} = \kappa_{\parallel}\left[\sin\delta\cos\delta\cos^2\psi(1-\beta) - \beta_1\sin\psi\right]$$

$$\kappa_{13} = \kappa_{\parallel}\left[\sin\psi\cos\delta\cos\psi(\beta-1) - \beta_1\sin\delta\cos\psi\right]$$

$$\kappa_{21} = \kappa_{\parallel}\left[\sin\delta\cos\delta\cos^2\psi(1-\beta) + \beta_1\sin\psi\right]$$

$$\kappa_{22} = \kappa_{\parallel}\left[\sin^2\delta\cos^2\psi + \beta\left(\sin^2\delta\sin^2\psi + \cos^2\delta\right)\right]$$

$$\kappa_{23} = \kappa_{\parallel}\left[\sin\delta\sin\psi\cos\psi(\beta-1) + \beta_1\cos\delta\cos\psi\right]$$

$$\kappa_{31} = \kappa_{\parallel}\left[\cos\delta\sin\psi\cos\psi(\beta-1) + \beta_1\sin\delta\cos\psi\right]$$

$$\kappa_{32} = \kappa_{\parallel}\left[\sin\delta\sin\psi\cos\psi(\beta-1) - \beta_1\cos\delta\cos\psi\right]$$

$$\kappa_{33} = \kappa_{\parallel}\left[\sin^2\psi + \beta\cos^2\psi\right]$$

[Alania 1978; 2002]

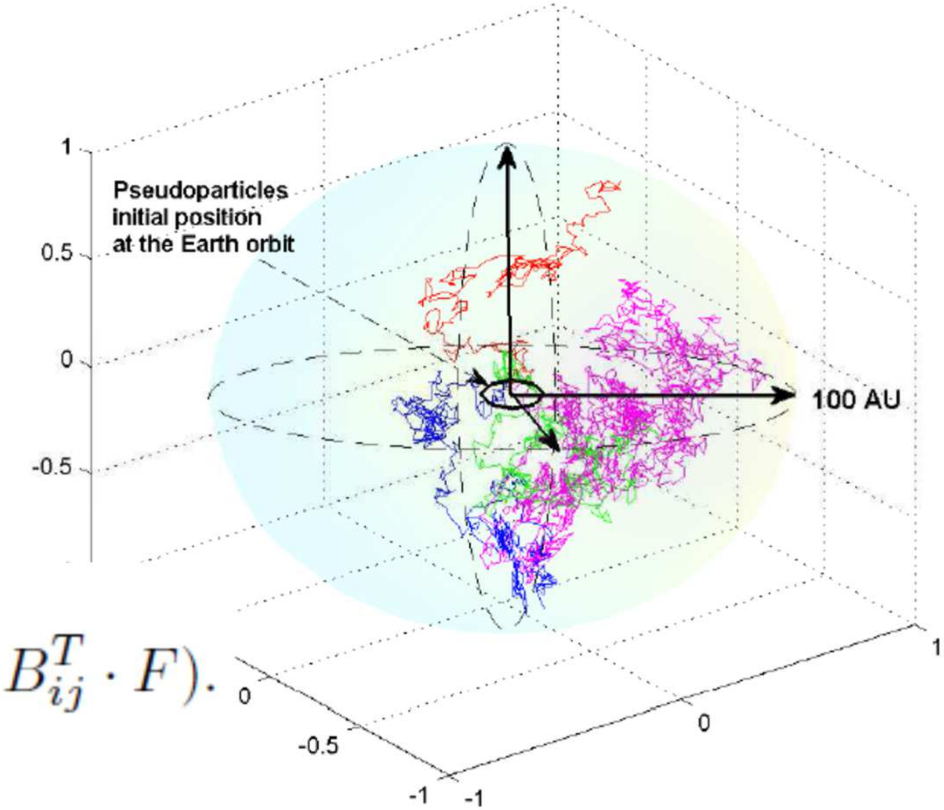
$$\kappa_{\parallel} = \kappa_0\kappa(\rho,\theta,\varphi)\kappa(R)$$

$$\kappa_{\parallel} \approx 10^{23}\ \mathrm{cm}^2/\mathrm{s}$$

Stochastic approach:

Backward in time

$$\frac{\partial F}{\partial t} = \sum_i A_i \frac{\partial F}{\partial x_i} + \frac{1}{2} \sum_{i,j} B_{ij} B_{ij}^T \frac{\partial^2 F}{\partial x_i \partial x_j},$$



Wawrzynczak, Modzelewska & Gil, 2015

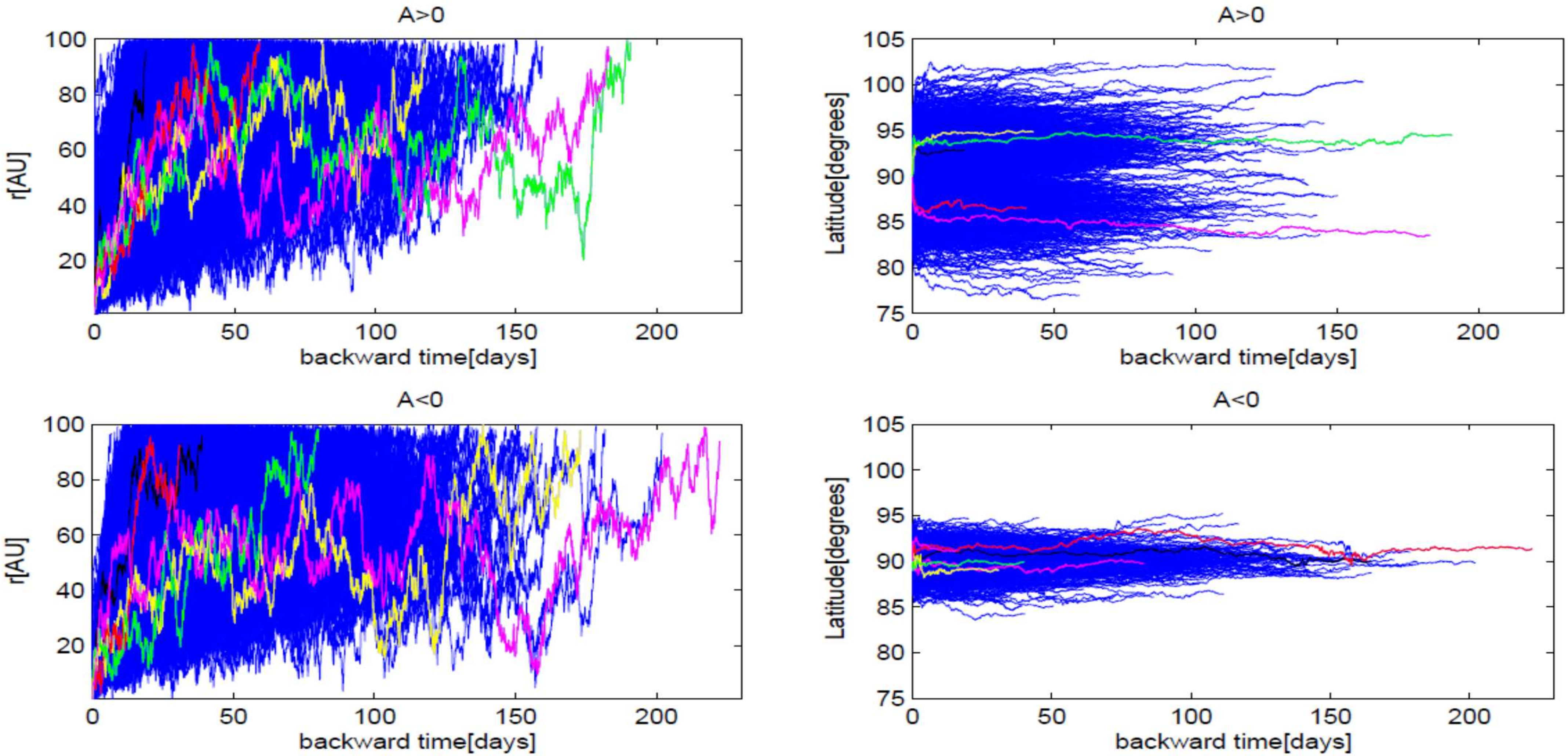
Forward in time

$$\frac{\partial F}{\partial t} = \sum_i \frac{\partial}{\partial x_i}(A_i \cdot F) + \frac{1}{2} \sum_{i,j} \frac{\partial^2}{\partial x_i \partial x_j}(B_{ij} B_{ij}^T \cdot F).$$

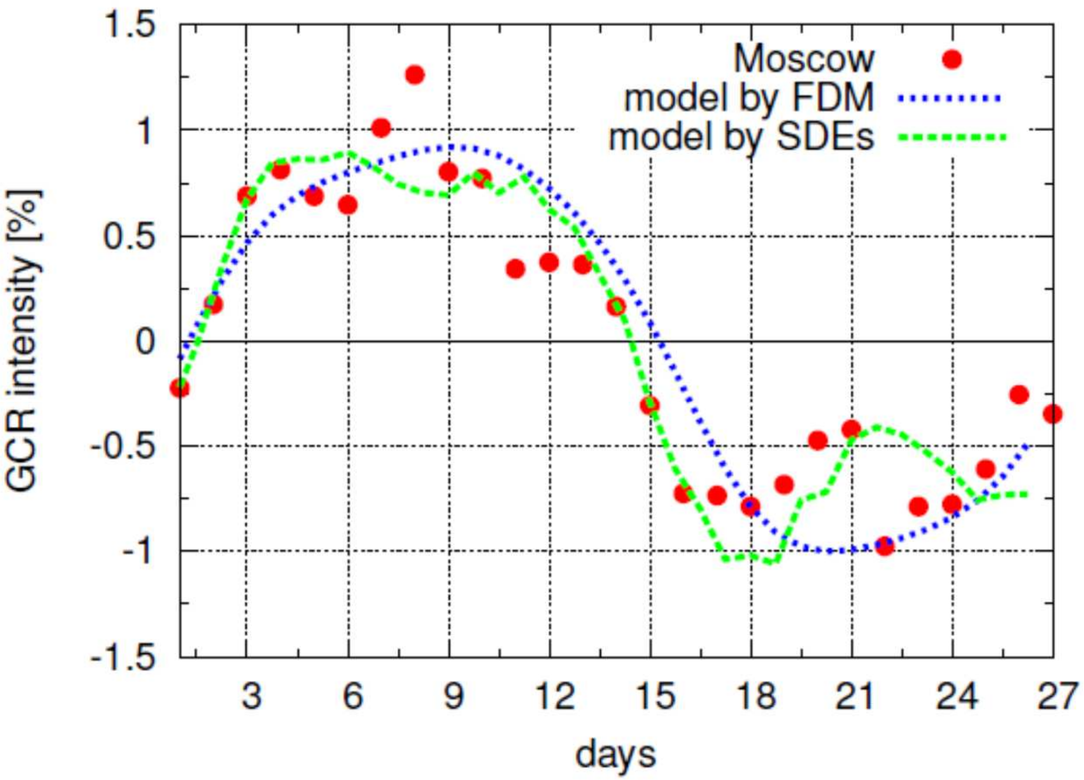
$$d\vec{r} = \vec{A}_i \cdot dt + B_{ij} \cdot d\vec{W},$$

$$dW_i = \sqrt{dt} \cdot dw_i,$$

Gardiner, 2009



Trajectories of the pseudoparticles with rigidity 10 GV. The specific colors highlight the trajectories of the sample pseudoparticles traced backward in time from the heliosphere boundary until they reach r = 1AU, θ = 90◦, φ = 180◦.



Changes of the expected amplitudes of the 27-dv of the GCR intensity at the Earth's orbit for the rigidity of 10 GV based on the solutions of the Parker transport equation by SDEs and FDM in comparison with the GCR intensity registered by Moscow neutron monitor for the 7 September - 3 October 2007.

Wawrzynczak, Modzelewska & Gil, 2015

$$U = U_0 \cdot \left(1 - 0.31\sin(\varphi + 6.10) + 0.06\sin(2\varphi + 0.82) - 0.10\sin(3\varphi - 1.04)\right)$$

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1. Global network of neutron monitors may be a useful tool for some indirect solar observations.
2. The rigidity spectrum of the 11-year variations of the GCR intensity is hard in the minimum epochs of SA (γ~0.6) when the exponent ν_y of the PSD of HMF is higher (ν_y~ 1.9), and is soft in the maximum epochs (γ~ 1.2), when ν_y is relatively lower (ν_y ~ 1.4).
3. We show the existence of clearly established quasi-periodicity with duration of three to four Carrington rotations period (3-4 CRP) in the changes of the amplitudes of the 27-day variations of GCR intensity, parameters of solar wind and solar activity. The 3-4 CRP recurrence is shaped by the combined: solar dynamo and differential rotation.
4. The A27 and A14 amplitudes during the SC minima depict a declining trend, which is associated with the weakening in the solar polar magnetic fields during the last four solar cycles.
5. The Fd rigidity spectrum exponent γ is the larger the higher are cut off rigidities of stations used in calculations. The dependence of the exponent ν of the PSD of the HMF turbulence upon frequency during Fd confirms the relationship between exponent γ and exponent ν
6. Solar anisotropy calculated from NMs data gives the opportunity to estimate the heliospheric modulation parameters: e.g., density gradients and diffusion coefficients used in modeling

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Conclusions

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Thank you!

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