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The Astroparticle Physics Conference
34th International Cosmic Ray Conference
July 30 - August 6, 2015
The Hague, The Netherlands

Ultimate Spectrum of Solar/Stellar Cosmic Rays

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INTRODUCTION



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- Distributions of solar events by a value of one or another observational parameter are a base for prediction of their occurrence in the past and future. Distributions should be limited by a maximal value of a chosen parameter due to physical reasons, therefore their direct extrapolation to large values is impossible. What are physical limits?
- The frequency distribution of most common proton events does not represent the extreme events. Solar proton events with > 30 MeV omni-directional fluence exceeding $6E9$ cm^{**2} are very rare. The extreme events should be close to their physical limits.
- We propose a physical approach to reconstruct the ultimate spectrum of solar/stellar cosmic rays (SCR) in a given point in the heliosphere (stellar sphere) basing on maximal value of magnetic field strength in active region and its characteristic linear dimension

SIMPLE ESTIMATES



$$\frac{B^2}{8\pi} = nE,$$

$$n = \frac{B^2}{8\pi E} = 8.3 \cdot 10^6 \text{ cm}^{-3},$$

$$N = nL^3 = 8.3 \cdot 10^{36} \text{ protons},$$

$$F = \frac{N}{4\pi R^2} = 2.9 \cdot 10^9 \text{ cm}^{-2},$$

$$E_{\text{max}} = \frac{e}{c} V \cdot B \cdot L = 100 \text{ GeV}$$

- $B=100$ Gs, $L=10E10$ cm, $V=100$ km/s
- Density n of >30 MeV protons
- Number N of >30 MeV protons
- Fluence F at $R=1$ AU
- Maximal proton energy

Solar Cosmic Ray Spectrum(Syrovatsky, 1961)



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- This spectrum was derived from general principles of thermodynamics, unrelated to specific
- parameters of acceleration mechanism.
- Average energy of particles increases under constant magnetic field pressure due to work of pressure forces and particle release from the acceleration region,
- κ - ratio of heat capacity of CR gas, 5/3 non-relativistic, 4/3 relativistic.
- The spectrum of particles released from the acceleration region

$$N(E_k)dE_k = -dn = \text{const} \cdot E_k^{-\gamma}$$

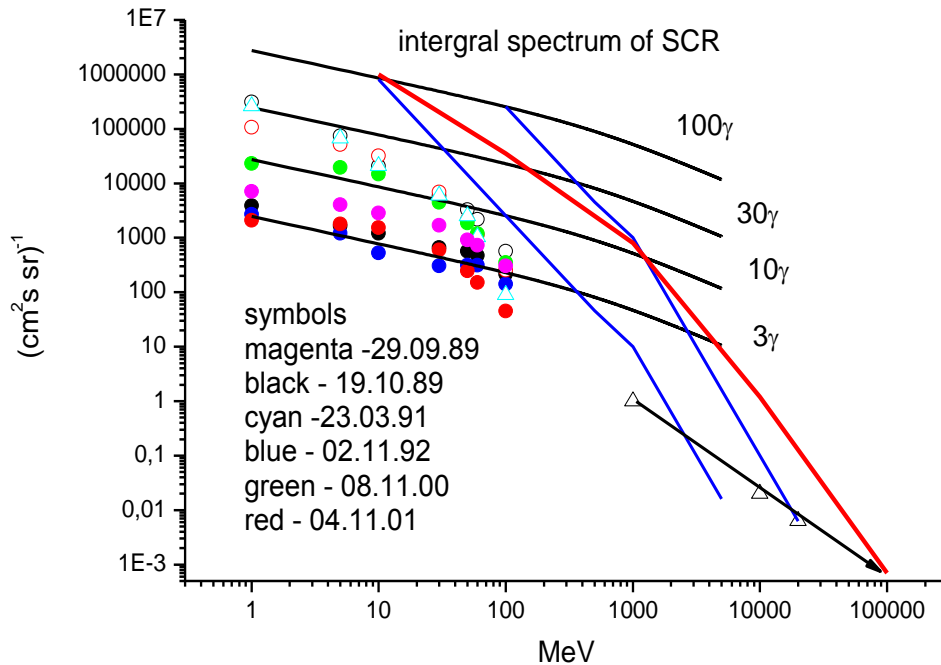
$$\gamma = (2\kappa - 1)/(\kappa - 1) = 3.5; = 5.$$

Normalization



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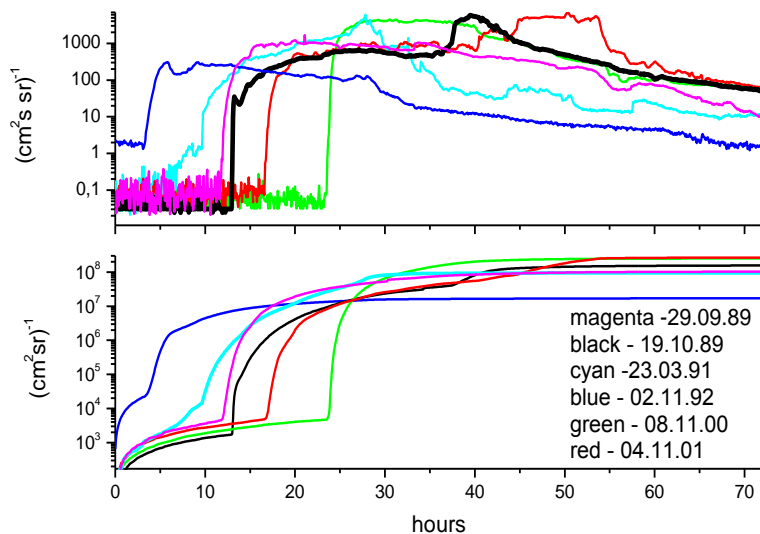
- The blue lines show the high energy part of the ultimate solar spectrum. Left and right blue lines are different by their normalization.
- The left spectrum is normalized to the upper limit flux of solar protons at 10 MeV (Miroshnichenko et al. 2013) and the right is normalized to the GCR spectrum at 20 GeV.
- The intensity of SCR may not be much higher at 20 GeV, otherwise the maximal energy of solar protons should be larger.
- A transition from relativistic to non-relativistic spectra was assumed at 2 GeV in both cases. The lower energy part of the spectrum is determined by propagation limits

Fluence accumulation



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- Time profiles of solar proton > 30 MeV intensities and accumulated fluences in the considered events are presented in the left figure.
- A ratio of fluence to maximal flux gives us a characteristic time, which is different for diffusive (1000 min) and storm (250 min) protons.
- We use the diffusive characteristic time of 1000 min to estimate ultimate fluences.

>30 MeV	Sep 29, 89	Oct 19, 89	Mar 22, 91	Nov 02, 92	Nov 08, 00	Nov 04, 01
FD	1.0E8	4.0E7		1.7E7	2.5E8	5.5E7
JD	1690	665		307	4440	980
TD (min)	1005	988	-	935	945	938
FS	-	9.4E7	9.6E7	-	-	2.7E8
JS	-	5826	6010	-	-	6870
TS (min)	-	267	264	-	-	647

ULTIMATE FLUENCES



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- We use the diffusive characteristic time of 1000 min to estimate ultimate omni-directional fluences.

	3 nT	10 nT	30 nT	100 nT
J(>30 MeV)	4.4E2	4.9E3	4.4E4	4.9E5
F(>30 MeV)	2.8E6	3.1E7	2.8E8	3.1E9
J(>200 MeV)	1.5E2	1.7E3	1.5E4	1.7E5
F(>200 MeV)	9.4E5	1.1E7	9.4E7	1.1E9

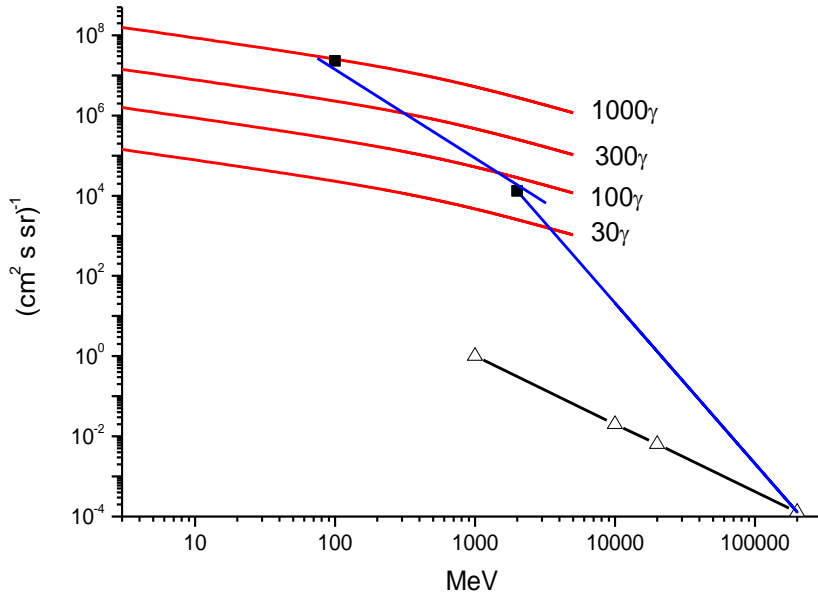
- Usoskin and Kovaltsov (2012) found 19 SPE candidates with $F(>30 \text{ MeV}) = 1-1.5E10 \text{ cm}^{**2}$ and no events with $F(>30 \text{ MeV}) > 2 E10 \text{ cm}^{**2}$ since 1400 AD.
- Kovaltsov et al. (2014) evaluated that extreme SPEs with $F(>200 \text{ MeV}) > 1E10 \text{ cm}^{**2}$ occur no more frequently than once per 10000 - 15000 years.
- These values serve as observational upper limits on the strength of SPEs on the timescale of tens of millennia, they are consistent with our estimates that the fluence resulted in the production of the cosmogenic isotopes was accumulated during several single events occurred within three months.

STELLAR COSMIC RAYS



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The ultimate spectrum of SCR for the maximal energy of proton acceleration 200 GeV and different values of the IMF strength.

- If a stellar magnetic field is a result of the dynamo mechanism, then the Stellar rotation is a source of magnetic field energy. Due to stellar magnetic activity stars lose their rotation energy.
- Young stars rotating quicker should have a greater values of magnetic field, flare frequency and Increasing of magnetic field in active region by about one order will lead to one order increasing of maximal energy of particle acceleration and two orders increasing of ultimate fluxes of SCR.

CONCLUSIONS



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- The ultimate spectrum of SCR near the earth orbit was reconstructed basing on the source spectrum (Syrovatsky, 1961) and propagation limits in the interplanetary space (Freier&Webber, 1963). The spectrum has two knee, one is at about 200 MeV due to propagation conditions and another at about 2000 MeV corresponds to transition from relativistic to non-relativistic regimes of particle acceleration.
- The spectrum proposed in (Miroshnichenko et al., 2013) provides smaller and larger intensities below and higher 2 GeV respectively. It does not account energy losses at high energy, transition to ultra-relativistic energies. Therefore to our opinion it does not represent the ultimate spectrum of solar protons at the earth orbit.
- We use the characteristic time of fluence accumulation obtained from the observations to derive an ultimate fluence of a single solar proton event (SPE). Our estimates are consisted with the observational upper limits on the strength of SPEs on the timescale of tens of millennia (Usoskin and Kovaltsov, 2012) and during the most active interval 1945 - 1995 of the last 2000 years (Cliver et al., 2014).
- The obtained numbers of >30 MeV and >200 MeV solar protons for a single proton event is not enough to explain the extreme solar particle event occurred in about 775 AD basing on the tree-ring chronology, a sequence of about twenty proton events may explain it.