The NMBANGLE PPOLA as a space weather-modeling tool: Application to GLE71 on 2012 May 17

Christina Plainaki[1,2], Helen Mavromichalaki[1], Monica Laurenza[1], Anastasios Kanellakopoulos[1], Maria Gerontidou[1], Marisa Storini[1], Anatoly Belov[3], Eugenia Eroshenko[3], Victor Yanke[3],

(1) INAF-IAPS, Via del Fosso del Cavaliere, 00133, Rome, Italy
(2) Nuclear and Particle Physics Section, Physics Department, National and Kapodistrian University of Athens, Athens Greece (emavromi@phys.uoa.gr)
(3) Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, RAS IZMIRAN Russia

Abstract

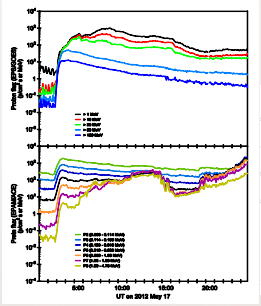
An updated version of the Neutron Monitor Based Anisotropic GLE Pure Power Law (NMBANGLE PPOLA) model, has been applied in order to derive the characteristics of GLE71 (on 2012 May 17), the spectral properties of the related Solar Energetic Particle (SEP) event, the spatial distributions of the high-energy fluxes of the primary solar protons at the top of the atmosphere and the time-evolution of the source location. Our modeling, based uniquely on the use of ground-level neutron monitor (NM) data, leads to the following main results and conclusions: the SEP spectrum related to GLE71 was rather soft during the whole period of the event manifesting some weak acceleration episodes only during the initial phase (at ~ 01:55-02:00 UT) and at ~02:30-02:35 UT and ~02:55-03:00 UT; the spectral index of the modeled SEP spectrum suggests a Coronal Mass Ejection (CME)-shock driven particle acceleration, in agreement with results based on the analysis of satellite measurements (see Li et al., 2013); during the very initial phase of GLE71, i.e. at 01:55-02:00 UT, the solar proton source at the top of the atmosphere was located above the northern hemisphere and as a result the asymptotic directions of viewing of the northern hemisphere NMs were more favorably located for registering the event than the southern ones; the spatial distribution of the solar proton fluxes at the top of the atmosphere, during the main phase of the event manifests a large variation along longitude and latitude; at the rigidity of 1 GV the maximum primary solar proton flux at the top of the atmosphere results to be of the order of particles 10^4 part. m^{-2} s^{-1} sr^{-1} GV^{-1}.

Scope of the current study

- to reconstruct the **SCR spectrum** in the **relativistic energy range** (>~500 MeV), at the top of the atmosphere
- to **provide an estimation of the SCR spectrum** in the lower energy range (<~500MeV), at the top of the atmosphere, through extrapolation of the model results
- to **explain the form of the GLE time-intensity profiles** during GLE71 on the basis of the solar particle arrival directions and the NM asymptotic directions of viewing and their variation with time
- to **provide quantitative information** on various **GLE characteristics** such as the **main direction of the anisotropic flux arrival** and the **SCR intensity** at the top of the atmosphere

Note that our results are based exclusively on the use of ground-based NM data;
→ ***our technique is completely independent from the in situ measurements analysis***, and therefore an a posteriori comparison of some model-derived specific quantities (e.g. the **solar proton spectrum**) with the in situ measurements can be used as a method in order to validate the model.

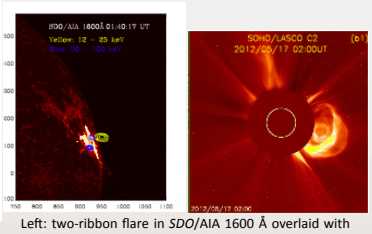
SEP event-associated observations



Integral proton flux recorded by EPS/ GOES (top) and EPAM/ACE (bottom)

Table 1 - SEP event associated solar conditions on 2012, May 17.

Active Region	Flare	CME	Radio sweeps	Shock passage (ACE)
11476 Location: N11° W76°	Class: M5/1f Onset: 01:25 UT Peak: 01:47 UT	Partial halo Onset:02:06 UT 1200 km/s	Type II (01:41-148 UT, 02:00-02:08 UT) Type IV	20/01:36 UT



Left: two-ribbon flare in *SDO*/AIA 1600 Å overlaid with the *RHESSI* HXR sources (from Li et al., 2013)
Right: CME observation by SOHO/LASCO (from Shen et al., 2013)

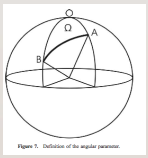
The NMBANGLE PPOLA model

The NMBANGLE PPOLA model couples **primary Solar Cosmic Rays (SCRs)** at the top of the Earth's atmosphere with the **secondary** ones detected at **ground level NMs** during **GLEs.** This model calculates dynamically the **SCR spectrum** and the **SCR flux spatial distribution**, outside the atmosphere **assuming a power law spectrum** for the primary SCR. The possible time variations, $\Delta N/N_0$, of the total neutron counting rate, N_0, observed at cut-off rigidity, R_c, at level h in the atmosphere at some moment t, are determined by the following expression (*Dorman 2004; Belov et al. 2005a; b; Plainaki et al. 2010*):

$$\frac{\Delta N(R_c,h,t,t_0)}{N_0(R_c,h,t_0)} = \int_{R_c}^{R_u} \frac{W(R,h,t_0)\cdot A(R,\Omega(R,t),t)\cdot b(t) R^{\gamma(t)}}{I_0(R,t_0)} dR$$

where *A(R,Ω,t):* is a dimensionless normalized function that describes the spatially anisotropic arrival of the SCR at 1 AU, given by:

$$A(R,\Omega,t) = \exp\left(-n_a(t)^2 \sin^2 \frac{\Omega(R,t)}{2}\right)$$

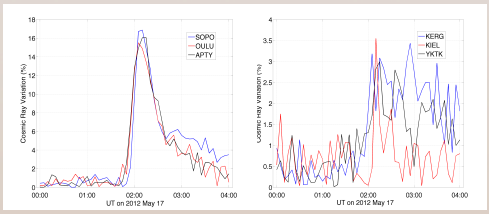


From *Plainaki et al., JGR, 2007*

W(R, h, t_0) : is the rigidity dependent coupling function between secondary and primary cosmic rays
γ(t): is the exponent of the power law primary SCR spectrum
Ω(R,t): is the solid angle defined by the vertical asymptotic directions of a NM at rigidity *R* and the location of the SCR source at the same altitude, as defined in *Plainaki et al. (2007)*
R_u : is the theoretical upper limit for the rigidity of the primary SCR particles
b(t): is the amplitude of the primary SCR differential flux (in protons m^{-2} s^{-1} sr^{-1} GV^{-1})
$I_0(R,t_0)$: is the Galactic Cosmic Ray (GCR) differential flux (in protons m^{-2} s^{-1} sr^{-1} GV^{-1})

Note that in our modeling **no location-dependent atmospheric density** is included; such an input could change the properties of the solar proton propagation inside the atmosphere, change the mean free path and the properties of the cascade, and result in variations of the ground level intensity-time profiles.

Ground-level Observations of GLE71



- The GLE was seen **mostly by polar** and some mid-latitude NMs.
- The polar NM of South Pole registered a maxima of ~17% at 02:05 UT.
- The **northern polar NMs of Oulu and Apatity** registered maximums of **~16%** (at 02:05 UT) and **~15%** (at 02:15 UT), respectively.

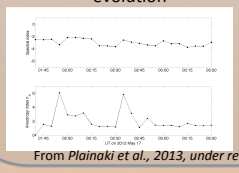
→ The **maximum rigidity** of the **primary solar protons** could not have been bigger than **~2.4 GV**

RESULTS: Primary SCR spectrum

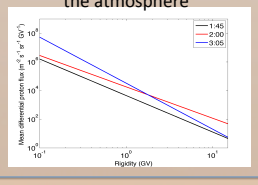
- a **rather soft spectrum** of accelerated protons→ spectral index varying between -3.8 and -2.1
- the **hardest spectrum** obtained in the time interval **01:55-02:10 UT→ in good agreement with *Li et al. (2013)* and** consistent with the typical range found by *Ellison and Ramaty (1985)* for **shock wave acceleration** in case of relativistic SEP events
- **possible existence** of two **small secondary episodes** of **solar particle acceleration**, at **02:30-02:35 UT** and **02:55-03:00 UT**.
- the **spectral index** in the main phase of the event (after 02:20 UT) is **~-3.8** → the **extrapolated NMBANGLE PPOLA results** do not **contradict the scenario of a possible shock wave acceleration**, suggested also by other studies (e.g. *Li et al. 2013; Gopalswamy et al. 2013; Shen et al 2013*)

Note that any information obtained by the model for the lower rigidity particles is the result of an extrapolation and should be treated with caution.

Spectral and anisotropy index evolution



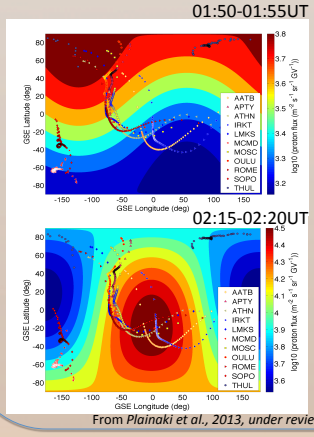
SEP spectrum at the top of the atmosphere



From *Plainaki et al., 2013, under review*

RESULTS: Spatial distribution of the primary SCR flux

01:50-01:55UT



02:15-02:20UT

From *Plainaki et al., 2013, under review*

At the time interval 01:50-01:55 UT
- the **asymptotic viewing cones of the northern polar NMs** of **Oulu** and **Apatity** intersect the regions of the increased primary proton fluxes, and as a result these NMs are rendered **more favorable for registering the GLE**

At the time interval 02:15-02:20 UT:
- the **difference** in the intensities registered at **South Pole** and **Oulu** are **smoothed**
- the **angular distribution** of the primary solar proton fluxes is **wide** (n_a=1.6)
- contrary to the initial phase of the event, when a **wide angular flux distribution** was also present, the primary solar proton intensities at this time interval **are increased over all longitudes and latitudes** (~10^4 $m^{-2}s^{-1}sr^{-1}GV^{-1}$). Therefore, although the northern NMs seem to be more favorable for the GLE registration, also the NMs of the southern hemispheres do register high count rates

CONCLUSIONS

- The **primary SCR spectrum**, at the top of the Earth's atmosphere, was **rather soft** with a **spectral index** (in rigidity) ranging between **-2.1 and -3.8**, in consistency with the estimations based on satellite observations (e.g. *Li et al. 2013*).
- The **primary SCR spectrum** calculated by our model **supports the CME-shock driven particle acceleration scenario**, although a direct flare contribution cannot be excluded.
- The **NM time-intensity profiles during GLE71** are interpreted on the basis of the primary SCR flux spatial distribution at the top of the Earth's atmosphere: in the initial phases of the event the northern NMs were more favorably positioned with respect to the GLE source, hence they registered the event prior to the southern ones.
- The **integral SCR fluxes** calculated by our model are **in good agreement with the GOES** observations and hence **a realistic estimation also of the >100MeV flux** value is provided.

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For more info contact:
christina.plainaki@iaps.inaf.it

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