Propagation and Acceleration of Protons during the First Ground Level Enhancement of Solar Cycle 24 on 17 May 2012

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A. Papaioannou[1,3], C. Li[2], O.E. Malandraki[3], E. Eroshenko[4], A.V. Belov[4], V. Yanke[4], E. Vashenyuk[5], Y. Balabin[5] and H. Mavromichalaki[1]

[1] Nuclear and Particle Physics Section, Physics Department , National and Kapodistrian University of Athens, GREECE
[2] School of Astronomy and Space Science, Nanjing University, Nanjing 210093, CHINA
[3] Institute of Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, GREECE
[4] Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation , IZMIRAN, RUSSIAN FEDERETION
[5] Polar Geophysical Institute, RUSSIAN FEDERATION

Abstract: The first Ground Level Enhancement (GLE) of solar cycle 24 was recorded on 17 May 2012. In this work we try to identify the acceleration source of energetic protons by combining in situ particle measurements from GOES 13, and solar cosmic rays registered by several NMs, as well as remote-sensing solar observations from SDO/AIA, SOHO/LASCO, and RHESSI. To this end, we derive the interplanetary magnetic field (IMF) path length and solar particle release time and we also present time-shifting analysis (TSA) for the first arriving particles that were detected at Earth by NMs. We demonstrate that the IMF direction was such that the NMs that were better connected, as derived by the particles asymptotic directions at 1-2.5 GV rigidity range, were Oulu (0.80 GV) and Apatity (0.65 GV) resulting into a prompt and fast rise in their counting rate. Furthermore, we discuss modeling results for GLE71 (i.e. spectrum, pitch-angle distribution and direction of anisotropy) obtained by the data made available via the Neutron Monitor Database (NMDB).

Background information of GLE71:

○ On 17 May 2012, the main sunspot group was active region AR11476. It produced a medium solar flare (M5.1), which started at 01:25 UT and peaked at 01:47 UT. The flare was accompanied by a halo CME. SOHO/LASCO pinpointed the beginning of the CME at 01:48 UT. Its linear speed was evaluated to be 1582 km s^{-1} [***Gopalswamy et al., 2012; 2013***]. Type III radio burst that signified the release of relativistic electrons into open magnetic field lines was spotted by STEREO A and B and also from Wind at L1. The electromagnetic emissions started at around 01:33 UT and ended at 01:44 UT [***Papaioannou et al., 2013***]. The type II burst, indicating a shock, was recorded by STEREO A and Wind at 01:40 UT, but was not seen by STEREO B. Signatures of this event were clearly seen in hard X-ray (HXR) emissions [***Li et al., 2013***]. GLE71 is the first event that has been recorded by multi-spacecraft at 1 AU (e.g. STEREO) [see ***Heber et al., 2013***]. Details of the background activity can be seen in *Figure 1*.

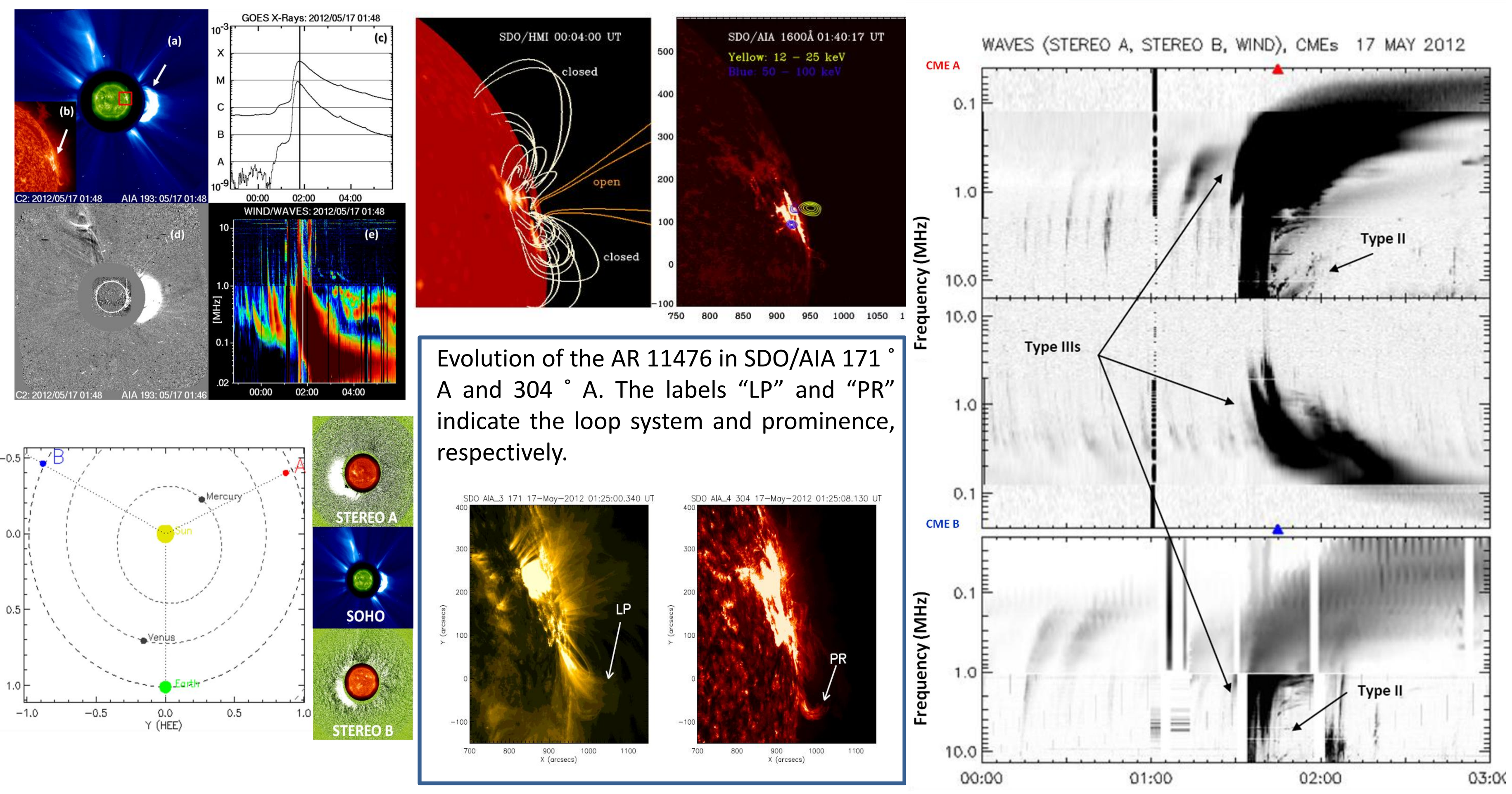


Figure 1. The M5.1 solar flare, together with soft X-rays, CME/LASCO C3 and Wind/Waves recordings (upper right figure). PFSS modeled coronal magnetic configurations of the AR 11476 (middle upper left panel) and two-ribbon flare in SDO/AIA 1600 ° A (middle upper right panel), overlaid with the RHESSI HXR sources. Radio spectrograms recorded by the SWAVES instruments onboard STEREO A (top panel), STEREO B (middle panel), and Wind/WAVES (bottom panel)

○ Timing of SEPs/GLEs with respect to flare emission (e.g., hard X-ray production, type III radio bursts) and CME signatures (e.g., type II radio bursts) is generally a tool for identification of particles acceleration source.

Neutron Monitor recordings:

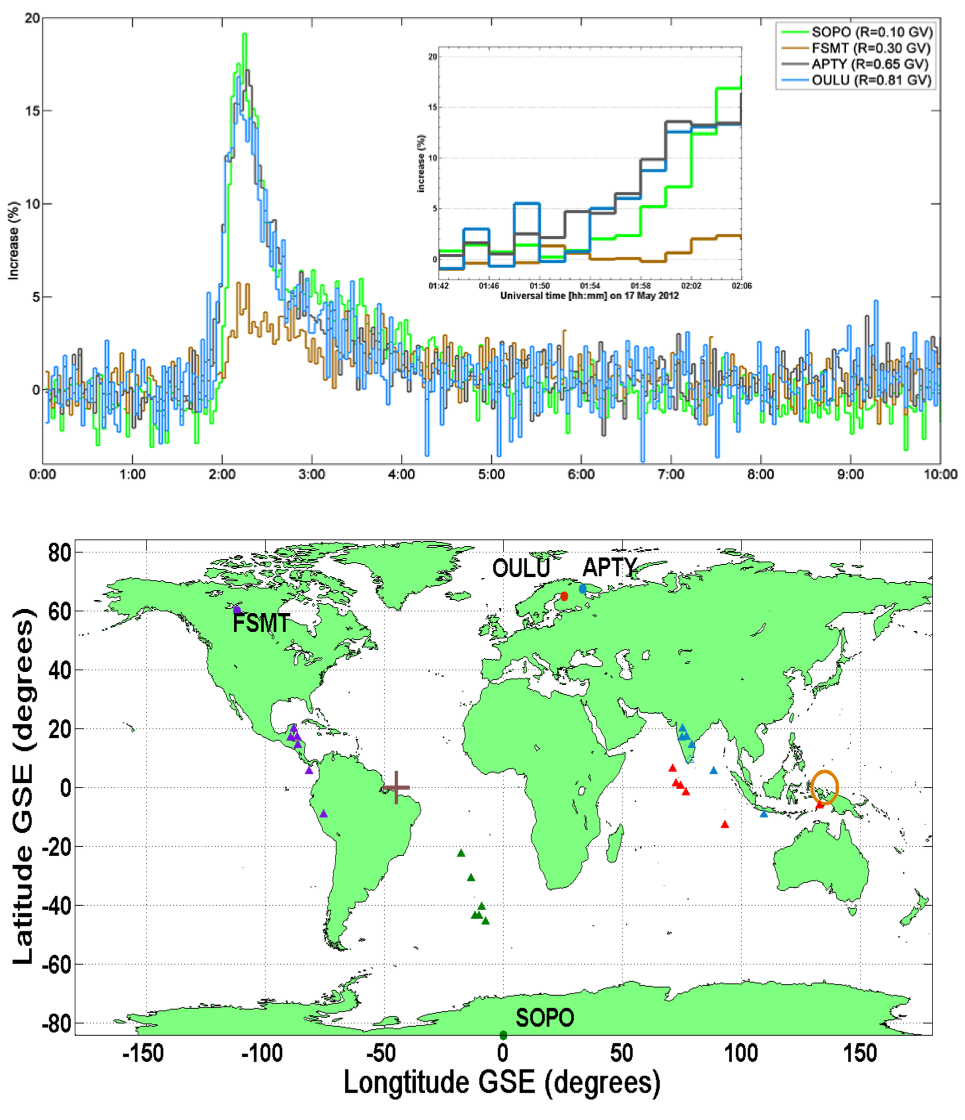


*Figure 2. **Top panel**: A The ground-level enhancement of 17.05.2012 (GLE71) as it was recorded by the OULU (blue), APTY (gray), FSMT (brown), and SOPO (green) NMs. A zoom of the rising phase of GLE71 as this was recorded by the NMs (the same color code has been applied) from 01:42 to 02:06 UT. **Bottom panel:** Viewing directions of neutron monitors in the GSE coordinates at 01:50 UT on 17 May 2012. Geomagnetic conditions were slightly disturbed (Kp=2; Dst=−34 nT)*

○ The rapid rise as shown by the **APTY and OULU NM** intensity time-profile (*Figure 2; **top panel***) indicates that relativistic protons had reasonable access to the Sun-Earth-connecting field lines.

○ Inspection of the NM data from various stations around the world showed that the event was recorded by NMs with a vertical cut-off rigidity up to ≈ **2 GV**, indicating that there were particles with this vertical cut-off rigidity. The Moscow NM, with a vertical cut-off rigidity of **2.43 GV**, recorded an increase of marginal significance that may or may not be related to GLE71. Therefore the rigidity of the particles did not exceed this threshold [***Papaioannou et al., 2013***].

○ The **APTY** and **OULU NMs** have **similar viewing directions**, which are very close to the nominal sunward direction (as is indicated by the empty-circle sign in *Figure 2; **bottom panel***). The **SOPO** and **FSMT NMs** present viewing directions close to the nominal anti-sunward direction (indicated by the plus sign in Figure5). The **APTY** and **OULU NMs** observed an **earlier onset** and **exhibited** a more **rapid rise** than the SOPO and FSMT NMs.

○The **SOPO NM** (together with SOPB – not shown), although shifted slightly further from the nominal sunward direction and closer to the anti-sunward one recorded the ***most intense flux*** during GLE71.

References:
> Gopalswamy et al., SH21A-2180, AGU Fall Meeting, 2012 > Gopalswamy et al., Ap. J. Letters, 765, L30, 2013
> Heber et al., 33rd ICRC, 2013 > Li et al., Ap. J., 770, 34, 2013 > Papaioannou et al., Sol. Phys., DOI 10.1007/s11207-013-0336-2, 2013
> Rufollo et al., Ap. J., 639, 1186, 2006 > Shen et al., Ap. J., 763, 114 , 2013 > Vashenyuk et al., 33rd ICRC, 2013

Data driven analysis of GLE71:

- Velocity Dispersion Analysis (VDA):

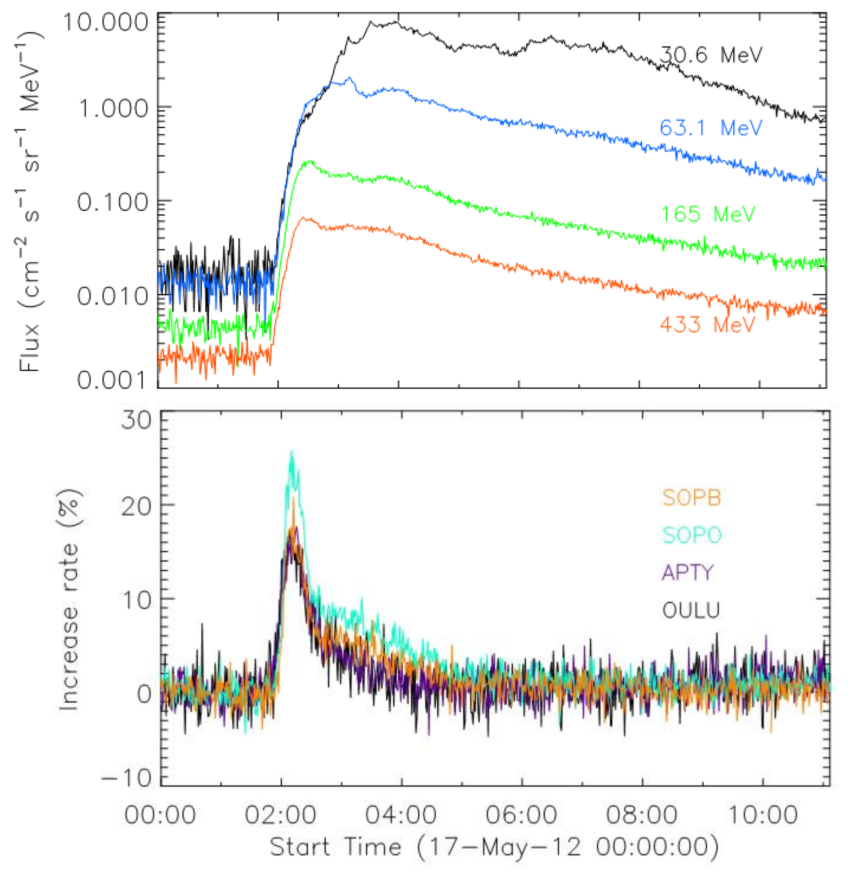


*Figure 3. **Top left panel**: Differential proton intensity profiles detected by the GOES 13 in four energy channels (30.6-433 MeV); **Bottom left panel:** SCR increases recorded by four NMs (SOPB, SOPO, APTY, OULU)*

○ Proton data in the energy range of ∼31 – 433 MeV obtained by GOES. Evidently, GOES 13 has recorded a fast rise in the flux of non-relativistic solar protons, followed by a slower decay, which was still ongoing on 2012 May 18 (*Figure 3*) (***Li et al., 2013***).

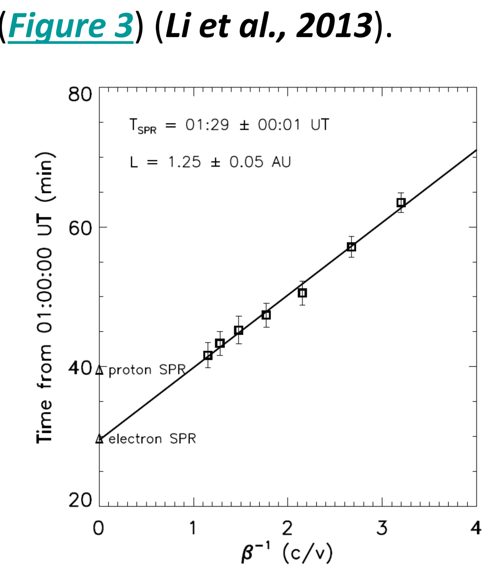


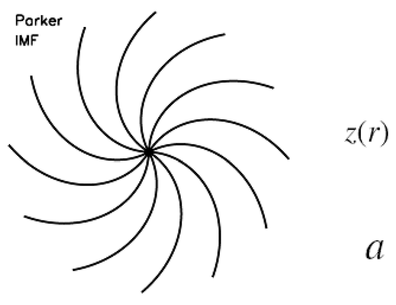
Figure 4. The straight line is the linear regression to the observations. The interception gives the SPR time and the slope corresponds to the IMF path length. The SPR times of electrons and protons are marked by triangles on the time axis.

○ Velocity dispersion analysis (VDA) (*Figure 4*) is based on determining the onset times of the event at a number of energies and presenting these onset times as a function of the inverse velocity of the particles at respective energies. The velocity dispersion equation at 1 AU can be written as:

$$t_{\rm onset}(E) = t_0 + 8.33\ \frac{\rm min}{\rm AU}\ s\,\beta^{-1}(E)$$

- Time-Shifting Analysis (TSA):

○ **Time-shifting analysis** (TSA) been performed for the particles of the APTY NM that presented the earliest onset time aiming at the identification of the relevant solar events. We have calculated the length of the nominal Parker spiral and assumed scatter-free propagation of the near relativistic protons (see ***Papaioannou et al., 2013***).



$$L(u_{\rm sw}) = z(r_{\rm S/C}) - z(R_\odot)$$

$$z(r) = \frac{a}{2}\left[\ln\left(\frac{r}{a} + \sqrt{1+\frac{r^2}{a^2}}\right) + \frac{r}{a}\sqrt{1+\frac{r^2}{a^2}}\right]$$

$$a = u_{\rm sw}/\Omega_\odot \qquad 2\pi\Omega_\odot^{-1} = 24.47\,{\rm d}$$

$$t_{\rm release} = t_{\rm onset} - \frac{L}{u} + 8.33\ ({\rm UT})$$

○ The a low-end energy limit of particles recorded by a NM station is **≈1GV** (i.e. 433 MeV). The corresponding mean velocity for such relativistic protons would be **u=0.73c**.

○ **APTY NM station** and obtained ***t_{onset}=1:50 UT***. The travel time of the relativistic protons of ≈ ***1 GV*** was calculated to be ***≈13 min*** and the corresponding anticipated SRT is ***≈ 01:45 UT***

Modeling GLE71:

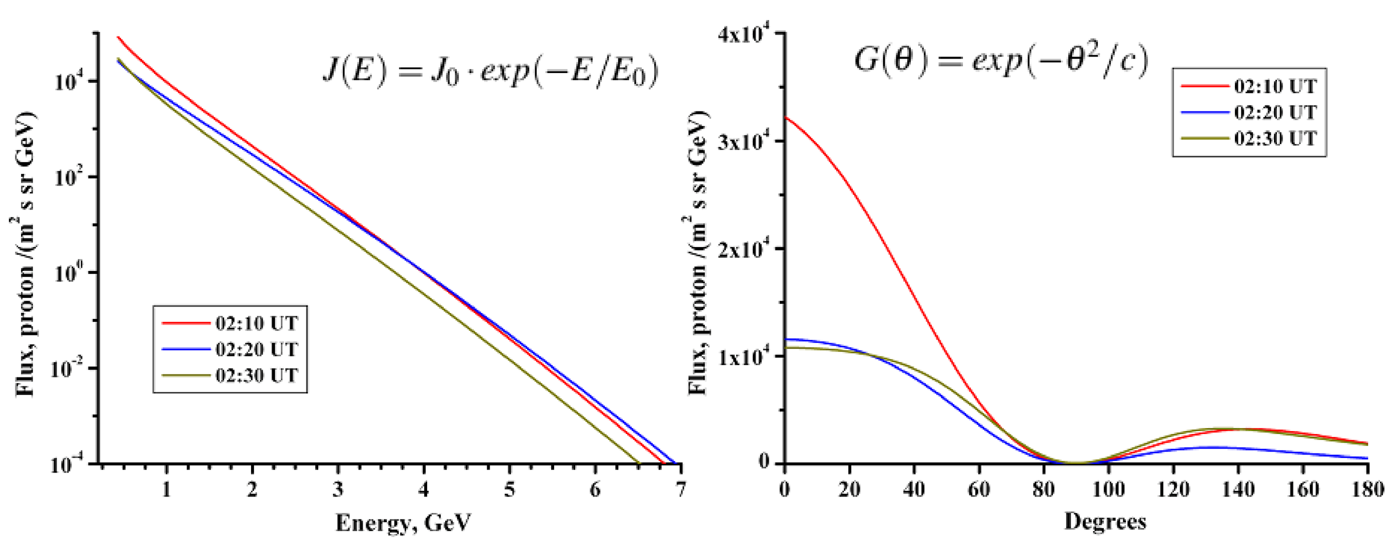


*Figure 5. **Left panel:** Derived spectra of Relativistic Solar Protons (RSP); **Right panel:** Pitch-angle distribution for the three moments of time.*

○ Modeling has shown that at ~ **90° pitch angles** an intensity gap is present.

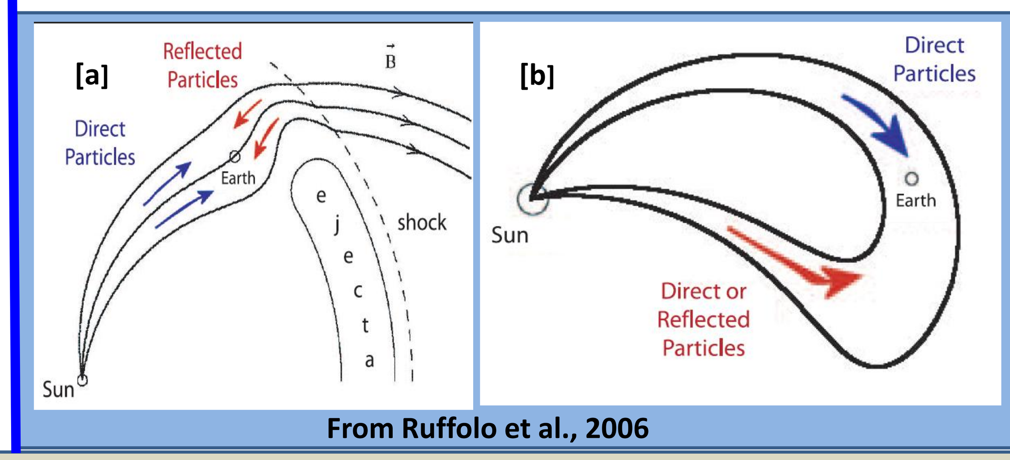
○ An **exponential form** of the **spectrum** is being derived for RSP [***Vashenyuk et al., 2013***].

Conclusions:

○ **GLE71** is the **first GLE of solar cycle 24**. It is the result of a medium-strength solar flare (M5.1) and its corresponding CME. The importance of this event lies in the fact that so far it is the only GLE of solar cycle 24, which underlines how modest, in terms of solar activity, this solar cycle has been so far.

○ The **GLE protons** injection takes place at **01:39 ± 00:02 UT** [**01:47 UT**, adding 8.33 min] (as deduced by VDA), their injection time is in accordance with the type II radio burst (at 1:40 UT) and the prominence eruption, which drives a high speed CME [the shock of the CME was formed at **≈4Rs** at **01:48 UT**], **the data driven analysis** (VDA & TSA) of GLE protons has shown that **most probably those are accelerated by the CME driven shock**.

○ **Modeling results** of **GLE71** imply that GLE protons of the prompt phase experienced **scatter-free propagation.**



From Ruffolo et al., 2006

A possible scenario for GLE71

Facts: SOPO NM is looking close to the anti-sunward direction and yet records the highest increase [**Papaioannou et al., 2013**]; There is a blob of hot plasma preceding the CME at ~ 40 min [**Gopalswamy et al., 2012**]; A scenario of CME-CME interaction has already been proposed [**Shen et al., 2013**].

Result: Particles should either be confined inside a loop [b] or mirrored because of an ejecta driven shock [a] [**Ruffolo et al., 2006**]. Evidence should be searched for in the pitch-angle distributions of relativistic electrons.

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Contact: atpapaio@astro.noa.gr

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