Scientific Aspects of Space Weather Services

Christina Plainaki

Planetary and Solar System Scientist

ASI – Italian Space Agency

Outline

SEPs: the major space weather phenomena in the near Earth space

Ground Level Enhancements (GLE) events: indicators of extreme space weather at 1 AU

Modeling: our tool for the study of SEP-GLE event coupling

An example: The NMBANGLE PPOLA model results and space weather implications

Discussion and ideas for future applications

Space Weather is a phenomenon taking place in the circum-terrestrial space, having its **origin at the Sun** and **its effects** in the **magnetosphere-exosphere-atmosphere environment.**

The **Solar Energetic Particles (SEP) events** represent one of the main components of the solar-driven space weather.

The SEP fluence peaks in the 1-100 MeV range in the interplanetary medium introducing an important radiation risk for space missions and resulting in elevated radiation dose rates and high frequency radio blackouts.

With criterion the observed bimodal distributions of different physical parameters, the SEP events are classified in **impulsive** and **gradual** ones.

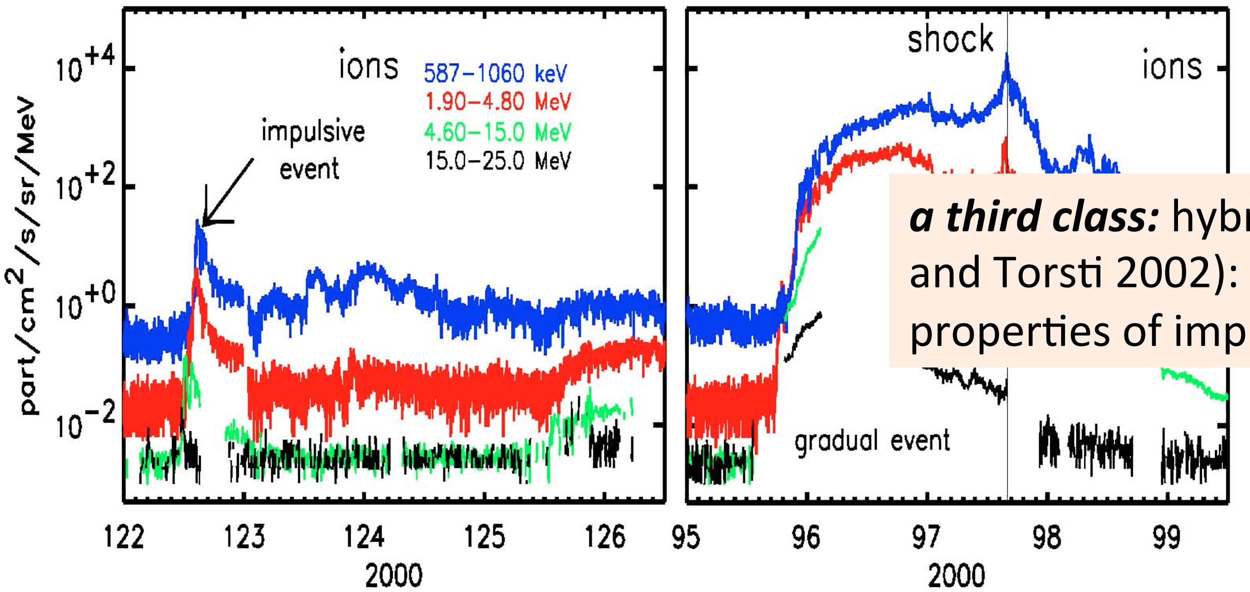
Impulsive SEP events

- short duration (from hours to days),
- electron rich
- ion abundances enhanced in ^{3}He related to the coronal abundances.

Gradual SEP events

- long duration (from days to week)
- proton rich
- ion abundances similar to the coronal ones (Reames 1999)

Proton intensity-time profiles, as measured by ACE/EPAM and IMP-8/CPME

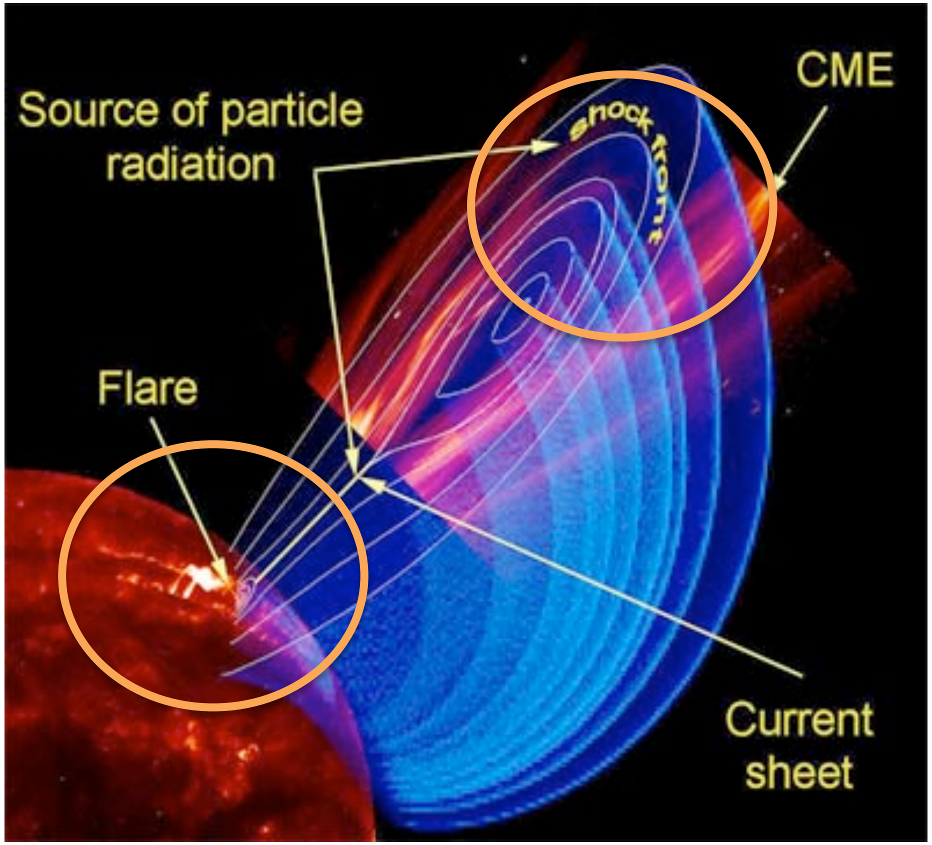


a third class: hybrid or mixed events (Kocharov and Torsti 2002): look like gradual but have properties of impulsive events.

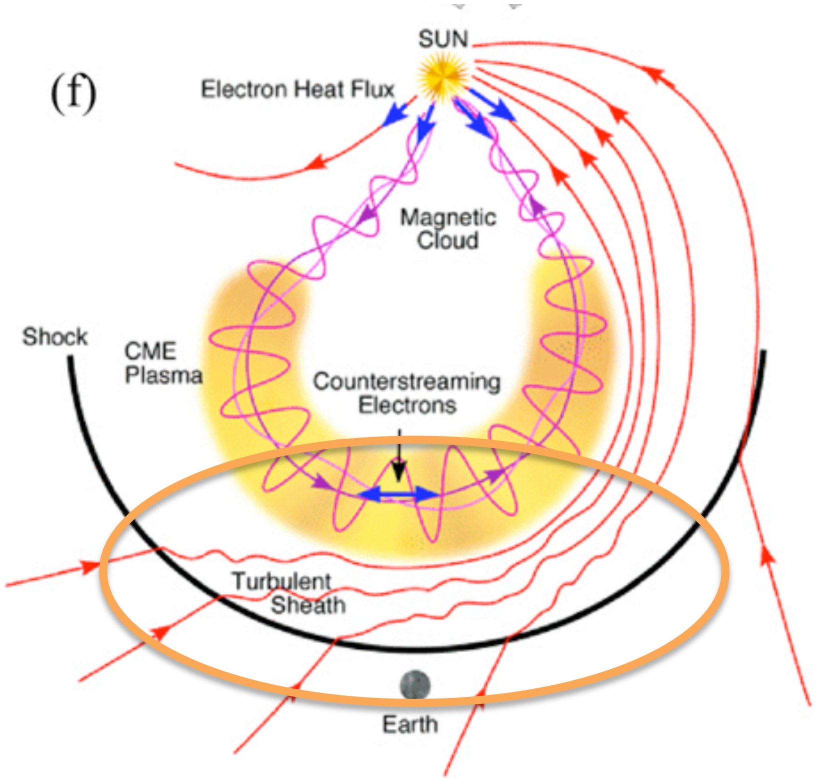
A. J. Tylka and M. A. Lee, ApJ 646, 1319 (2006)

Impulsive SEP are accelerated in the flare regions.

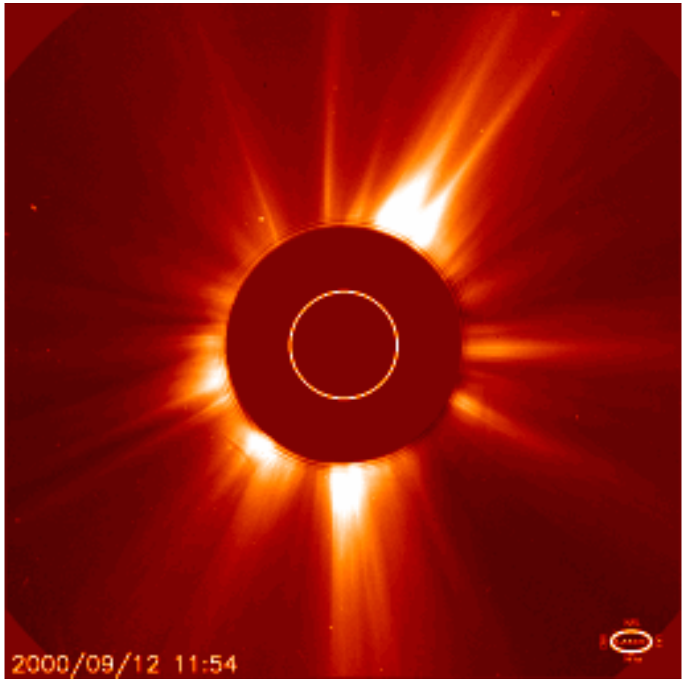
Gradual SEP are accelerated at coronal and interplanetary shocks mainly related to Coronal Mass Ejections (CMEs).



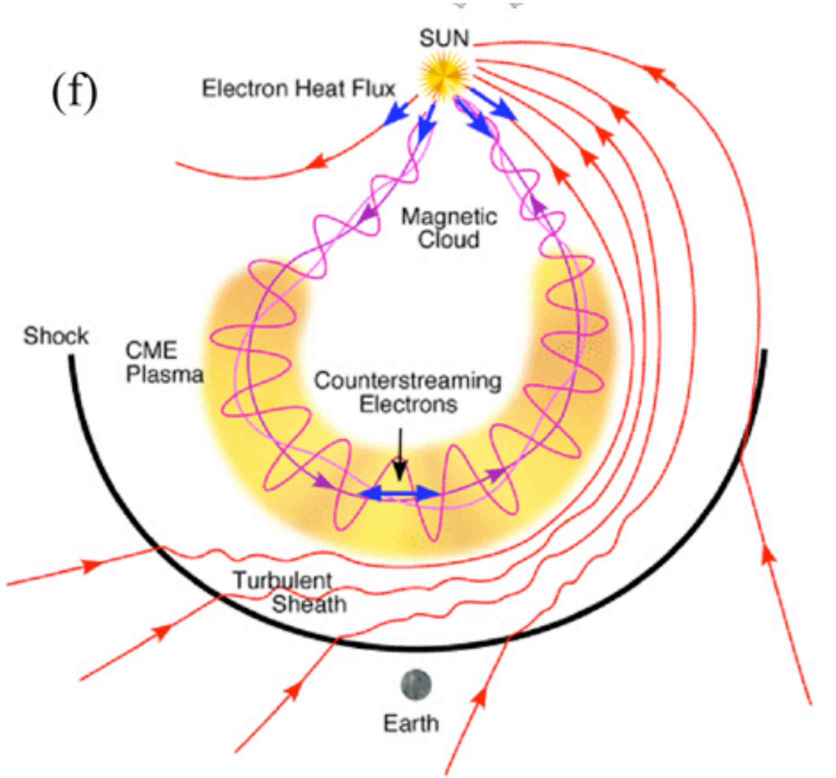
Credit: SAO and SOHO (ESA/NASA)



Zurbuchen & Richardson (2006)



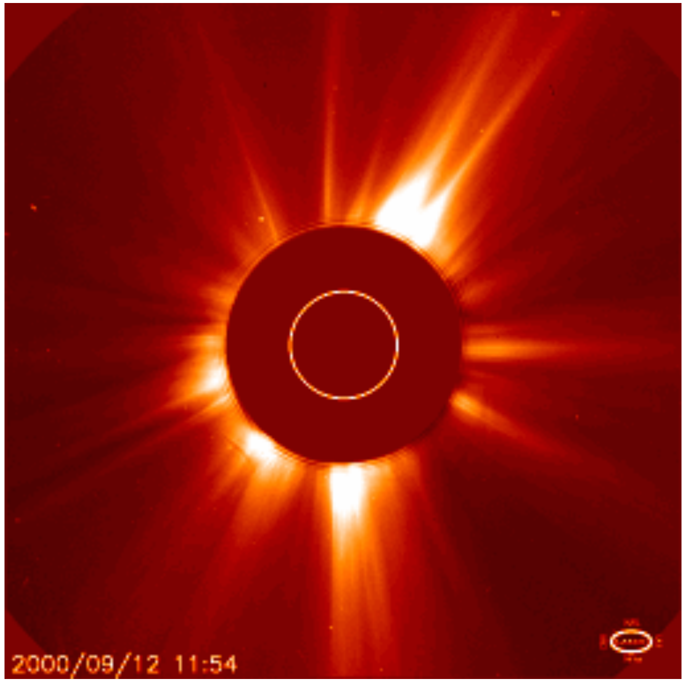
Credit: NASA



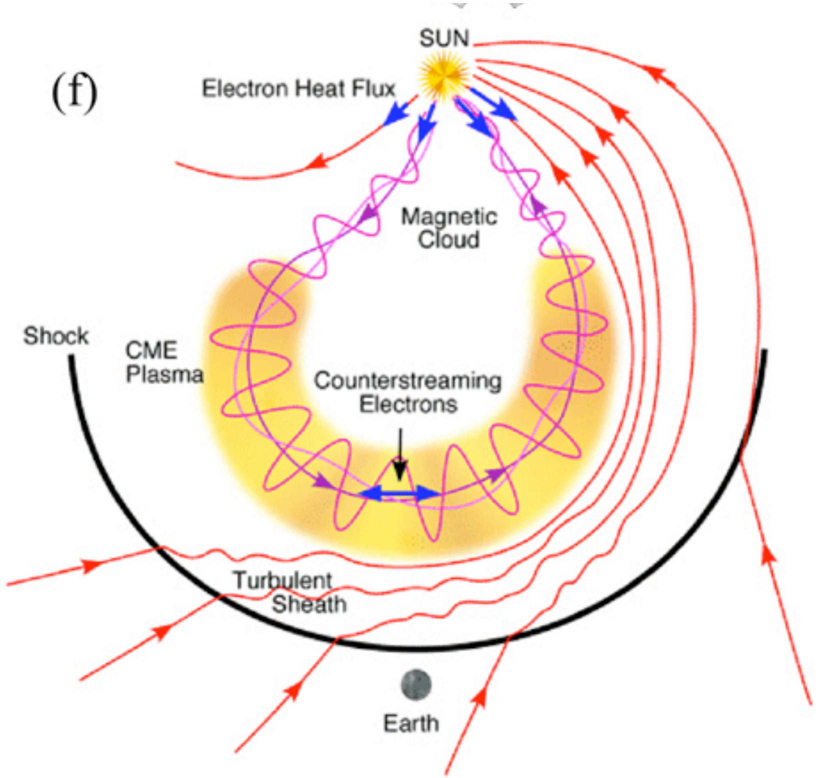
Zurbuchen & Richardson (2006)

An **ICME** is the **interplanetary CME** counterpart. A fast ICME usually drives a fast forward shock.

Between the shock and the ICME a **shocked sheath region** is located, characterized by elevated temperatures and densities, and rapidly varying magnetic field.



Credit: NASA



Zurbuchen & Richardson (2006)

An ICME is **geoeffective** – meaning it produces a **geomagnetic storm** - if
- it arrives at the Earth;
- it contains a suitable magnetic field orientation: strong and long lasting **southward IMF component**.

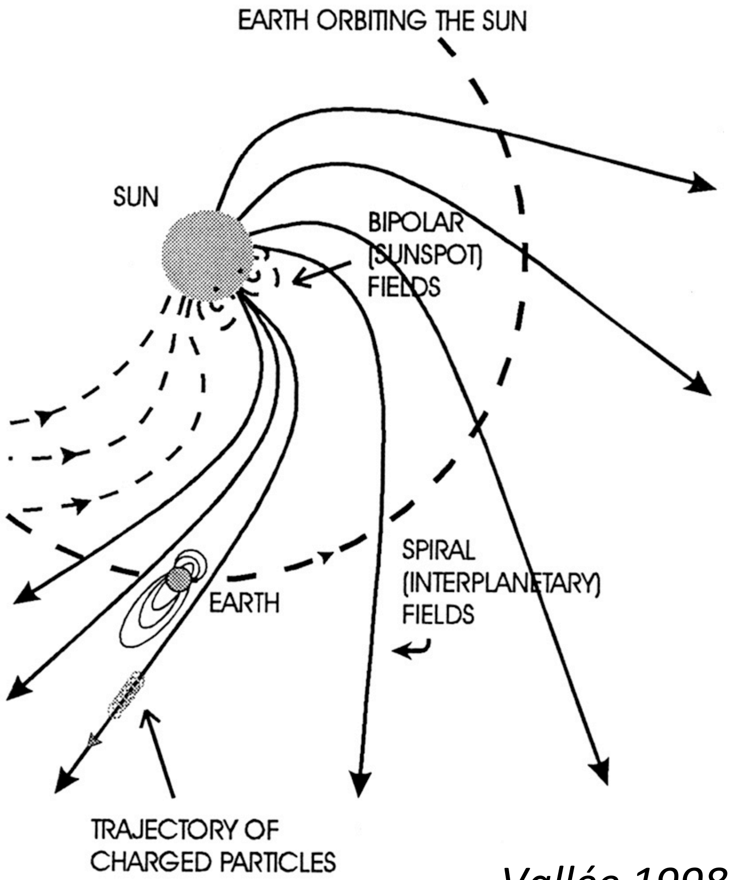
Between the shock and the ICME a **shocked sheath region** is located, characterize by elevated temperatures and densities, and rapidly varying magnetic field.

The intensity-time profiles of SEP events result from the evolution of the particle population in a set of flux tubes that sweep over the observer.

The intensity-time profiles depend on the observer's longitude (and latitude)

For typical solar wind conditions → good magnetic connection to an observer at Earth for an **impulsive SEP event** is ~ W50-W70.

Gradual SEP events, however, are observed wide-spread over a broad range of solar longitudes regardless of the associated solar flare location



Vallée 1998

The motion of charged energetic particles from their source to the observer is in general constrained by the Parker spiral pattern of the IMF.

Ground Level Enhancement (GLE) events as an indicator of extreme space weather

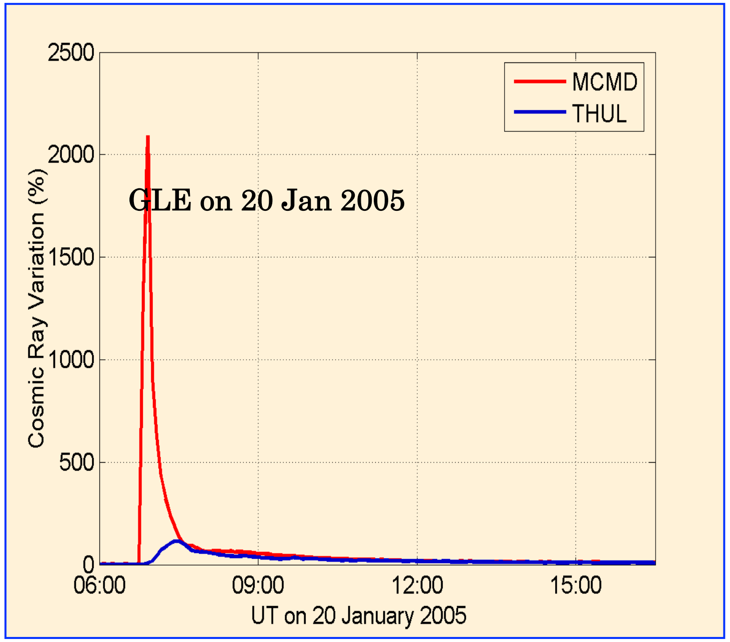
Ground-level enhancements (GLEs) are short-term increases of the cosmic ray intensity registered at the ground by particle detectors (ionization chambers, muon, and neutron monitors), related to the arrival in the terrestrial environment of solar relativistic particles.

GLE events are related to the most energetic class of solar energetic particle (SEP) events, associated with both solar flares and coronal mass ejections and requiring acceleration processes that produce particles with energies ≥500 MeV upon entry in the Earth's atmosphere.

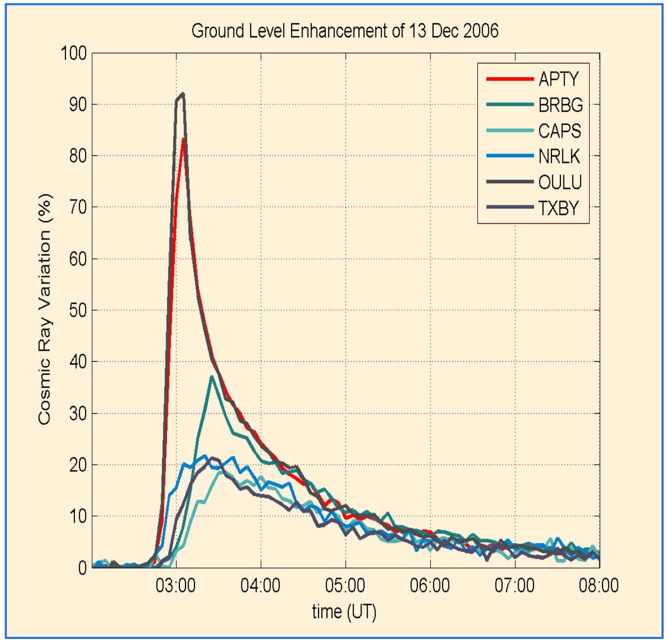
Ground Level Enhancement (GLE) events as an indicator of extreme space weather

Ground-level enhancements (GLEs) are short-term increases of the cosmic ray intensity registered at the ground by particle detectors (ionization chambers, muon, and neutron monitors), related to the arrival in the terrestrial environment of solar relativistic particles.

Examples of GLE events recorded at ground-based Neutron Monitor detectors



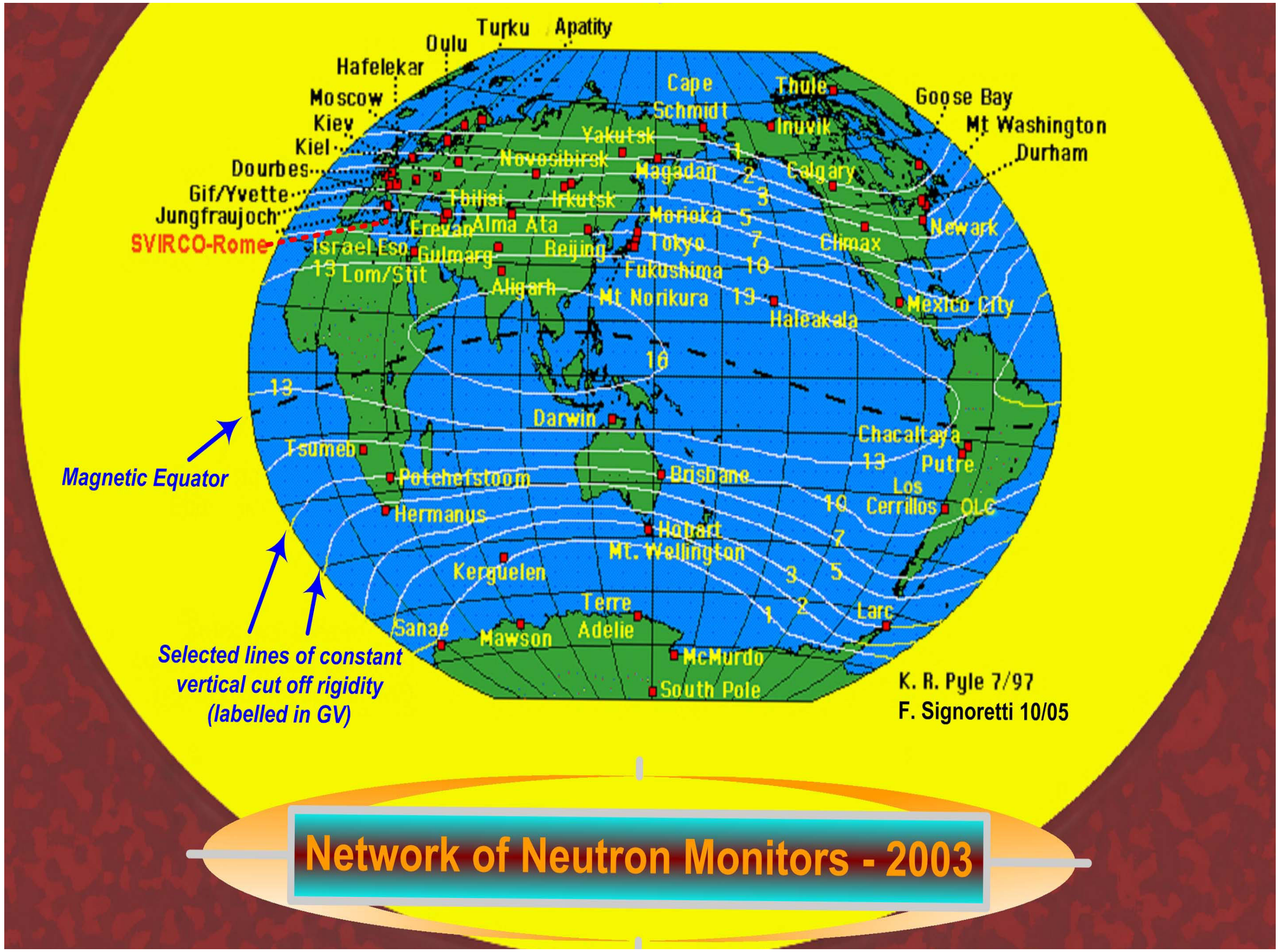
Plainaki et al., JGR, 2007



Plainaki et al., AdSR, 2009a

The Neutron Monitor Network

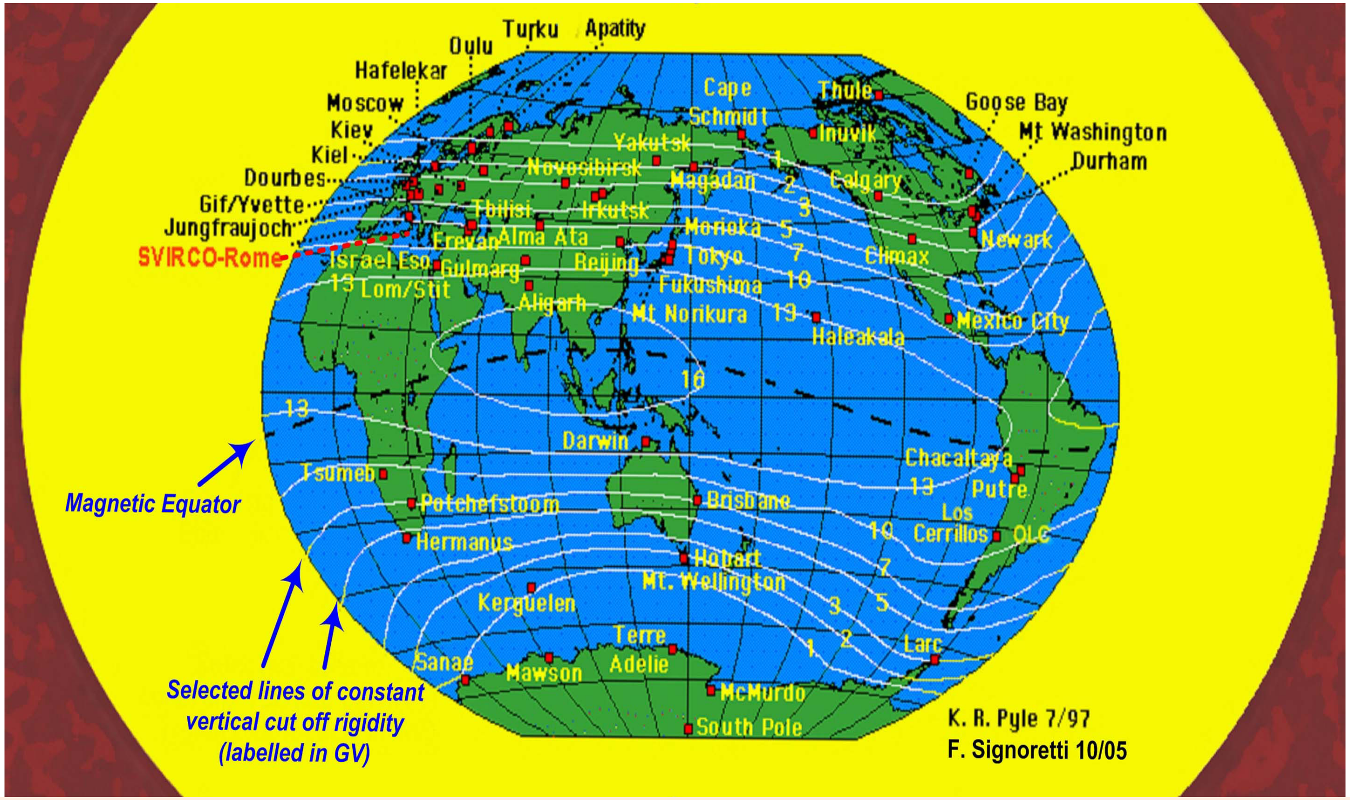
Because the **intensity of cosmic rays** hitting the Earth's atmosphere is in general not uniform, it is important to have **neutron monitors placed at different locations** in order to obtain a complete picture of the **spatial and energy distribution of the primary populations**.



Courtesy of Marisa Storini (INAF-IAPS)

The Neutron Monitor Network

Because the **intensity of cosmic rays** hitting the Earth's atmosphere is in general not uniform, it is important to have **neutron monitors placed at different locations** in order to obtain a complete picture of the **spatial and energy distribution of the primary populations**.

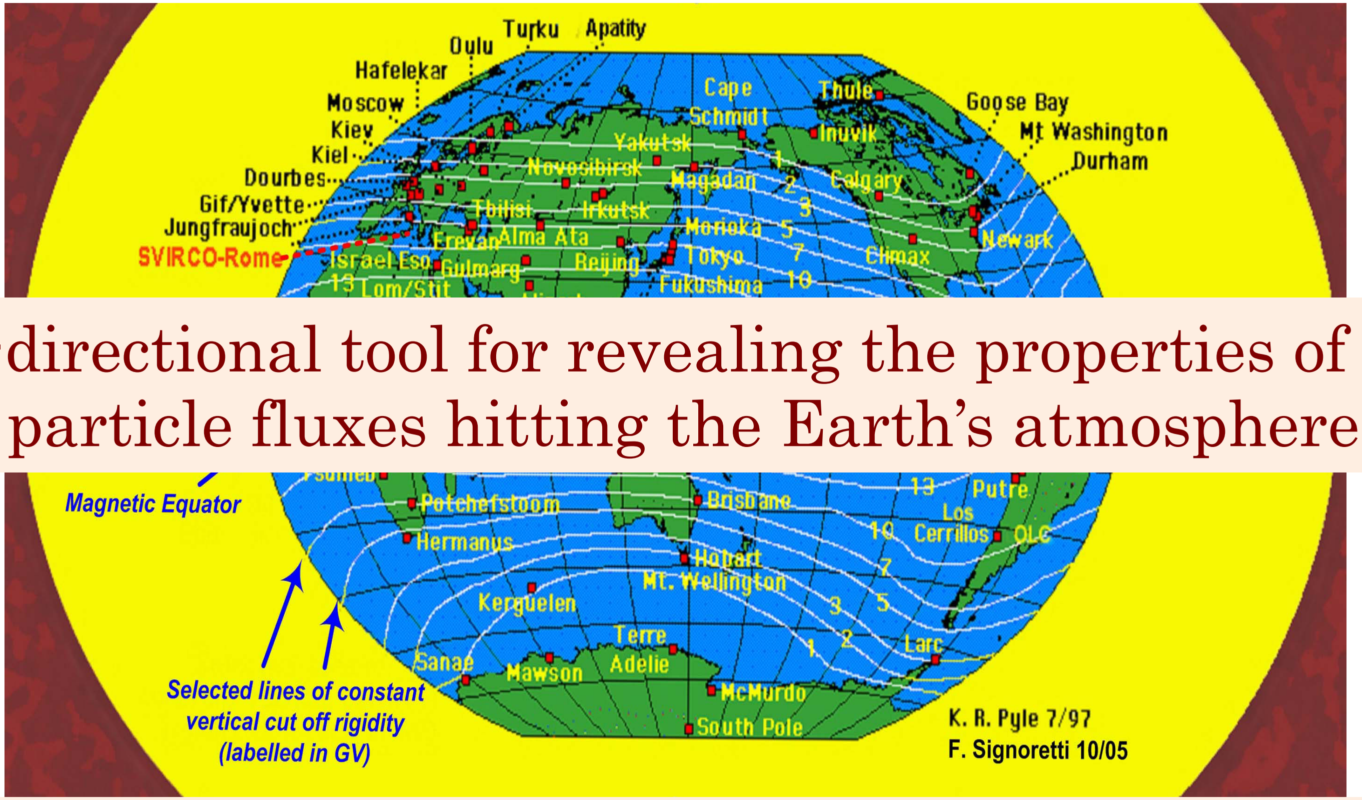


At each NM location, the detected secondaries:

- correspond to primaries with energies covering **only a specific part of the primary spectrum**, depending on the magnetic cut-off rigidity at this location
- correspond to primaries coming from a specific **set of directions** in the sky

The Neutron Monitor Network

Because the **intensity of cosmic rays** hitting the Earth's atmosphere is in general not uniform, it is important to have **neutron monitors placed at different locations** in order to obtain a complete picture of the **spatial and energy distribution of the primary populations**.



A multi-directional tool for revealing the properties of primary particle fluxes hitting the Earth's atmosphere

At each NM location, the detected secondaries:

- correspond to primaries with energies covering **only a specific part of the primary spectrum**, depending on the magnetic cut-off rigidity at this location
- correspond to primaries coming from a specific **set of directions** in the sky

The Neutron Monitor Network as a tool for revealing the relativistic SEP properties

The GLE data recorded by the worldwide Neutron Monitor (NM) Network are a useful resource for space weather modeling during solar extreme events.

Several techniques for modeling the dynamical behavior of GLEs throughout their evolving are presently available (e.g. *Shea and Smart, 1982; Humble et al., 1991; Belov et al., 2005; Bombardieri et al., 2007; Plainaki et al., 2007; Vashenyuk et al., 2011; Mishev et al., 2014; Plainaki et al., 2010; 2014*).

Basic idea: the responses of an adequate number of ground level NMs, are modeled to determine a best fit SEP spectrum and spatial distribution at 1 AU, during a GLE event.

Key point: The functions that are being used are chosen as to represent the **physical processes** involved in the **particle rigidity distribution and propagation** as well as the **response of the atmosphere** to the incoming SEP fluxes.

The Neutron Monitor Network as a tool for revealing the relativistic SEP properties

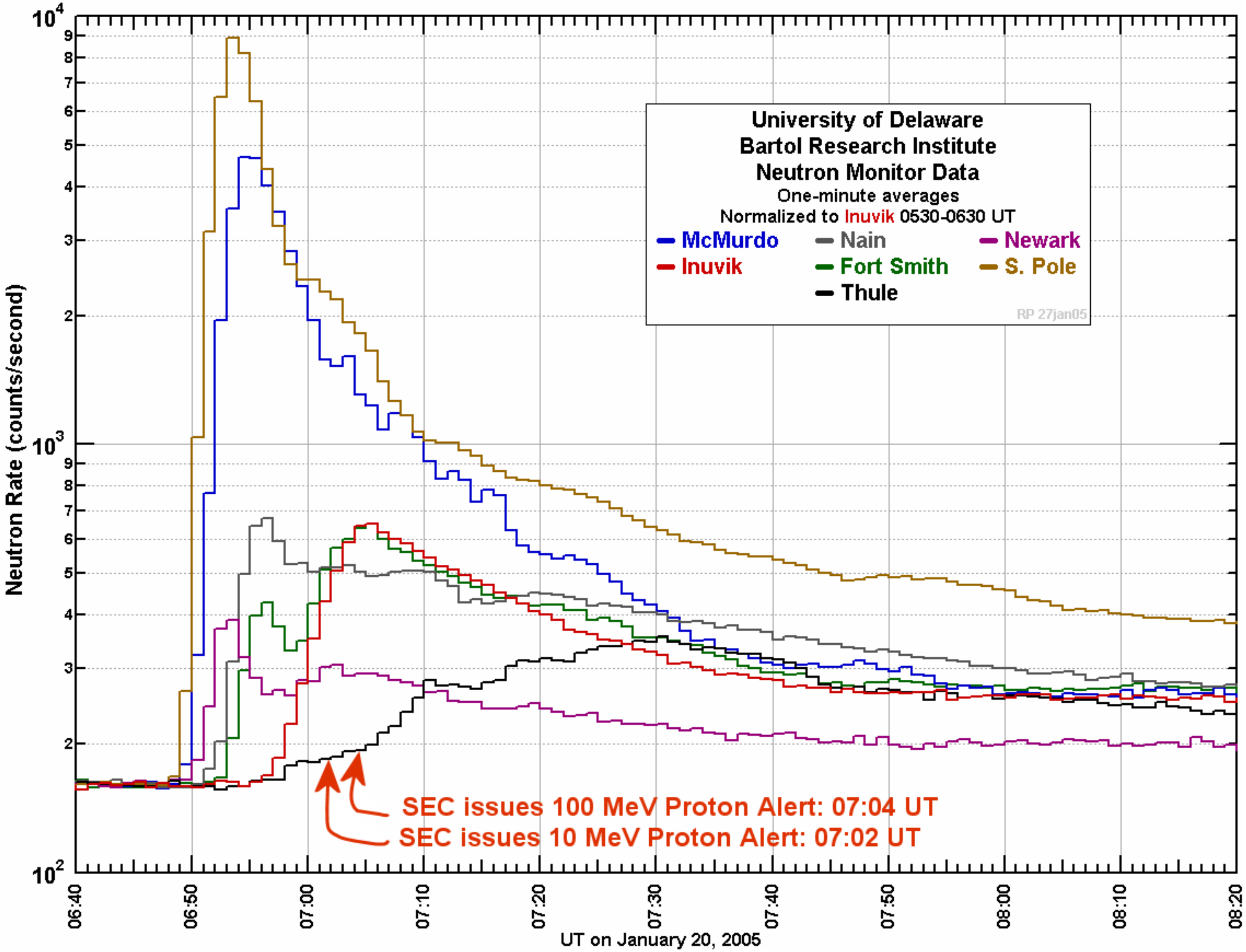
The GLE data recorded by the worldwide Neutron Monitor (NM) Network are a useful resource for space weather modeling during solar extreme events.

Technically, the accurate modeling of a GLE event depends on:

- the data quality of each NM
- the number of the NMs used in the analysis and
- their spatial distribution around the world;

For example, in order to avoid a biasing of the modeling-results, data originating from NMs that are almost equally distributed between the two hemispheres should be used.

Neutron Monitors for forecasts: Example



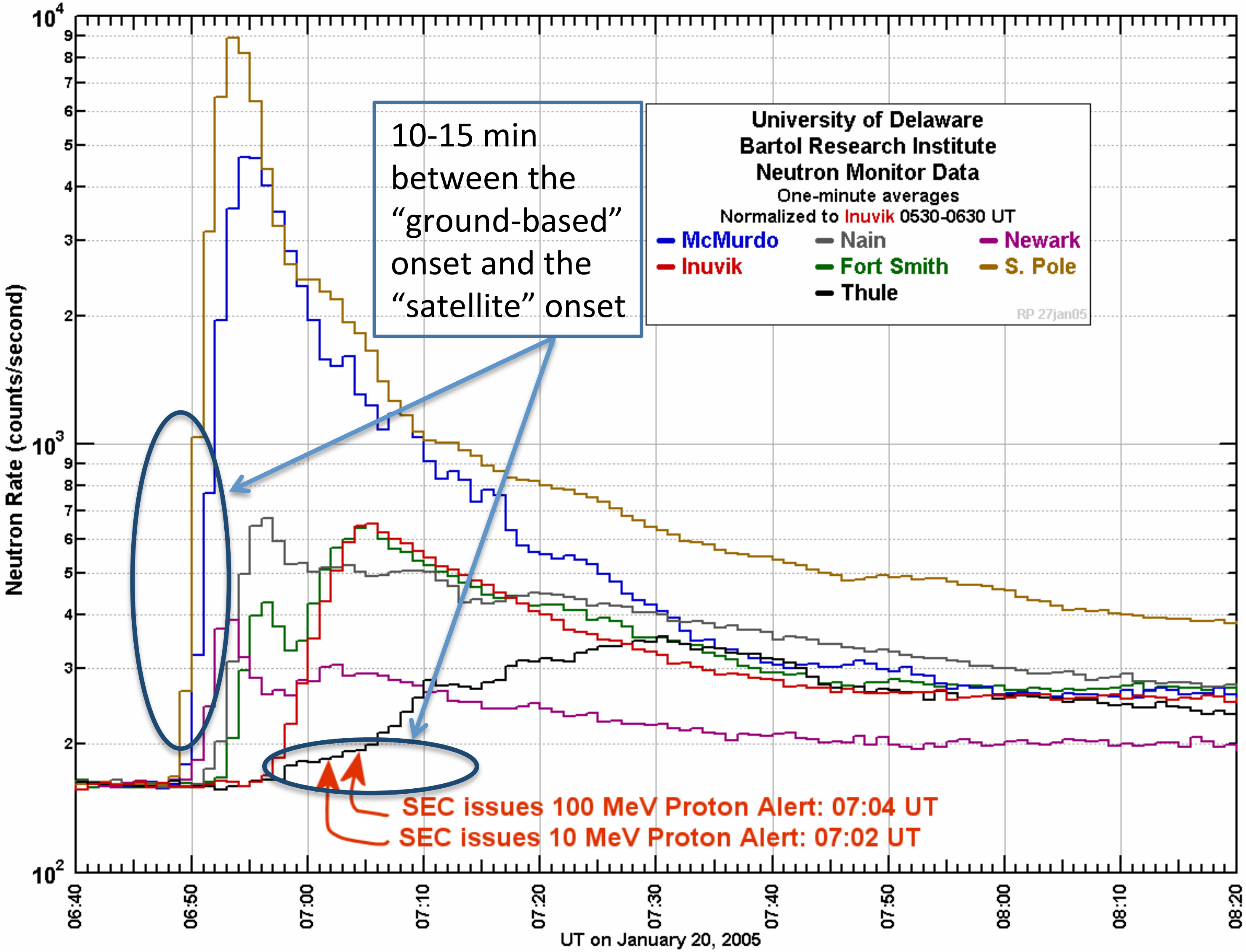
In the January 20, 2005 GLE, the earliest neutron monitor onset preceded the earliest Proton Alert issued by the Space Environment Center by 14 minutes.

After:

J.W. BIEBER

ICRC' 07 WORKSHOP

Neutron Monitors for forecasts: Example



In the January 20, 2005 GLE, the earliest neutron monitor onset preceded the earliest Proton Alert issued by the Space Environment Center by 14 minutes.

After:

J.W. BIEBER

ICRC' 07 WORKSHOP

Modelling: our tool for understanding space weather

an example

An example of how modeling contributes in our better understanding of space weather:

The Neutron Monitor-Based Anisotropic GLE Pure POwer LAw (NMBANGLE PPOLA) model

The NMBANGLE PPOLA model was based on **Dorman's coupling coefficient method** and **couples SEP** at some altitude in the Earth's atmosphere with their **secondary products** detected at ground level NMs during GLEs (*Plainaki et al., 2010*).

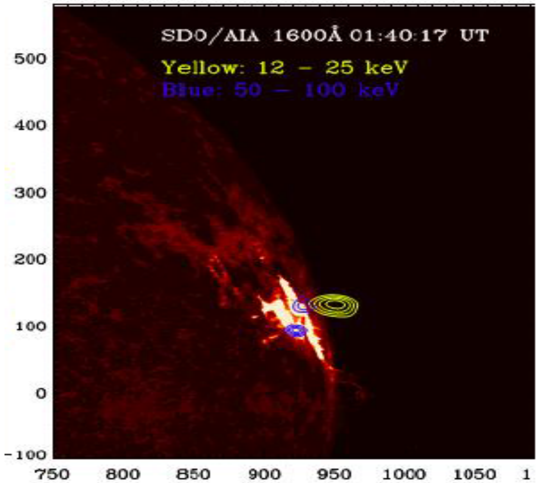
This model calculates dynamically the **SEP spectrum** and the **SEP flux spatial distribution**, at some altitude of the Earth’s atmosphere **assuming a power law spectrum** for the SEP.

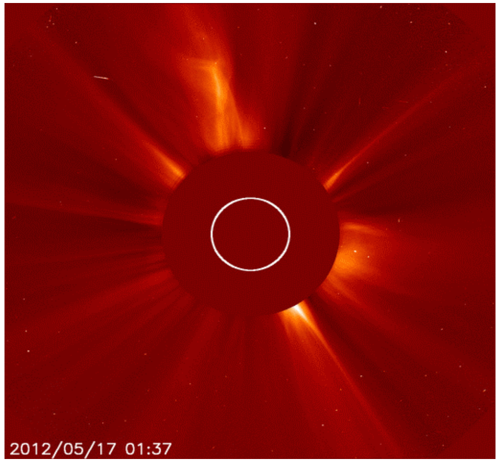
Overall output of the model: A multi-dimensional picture of the whole SEP/GLE event.
The SEP flux characteristics in space and time are estimated based on their propagation in the Terrestrial atmosphere and final registration at the ground, through their secondaries.

Model application to two different SEP/GLE events

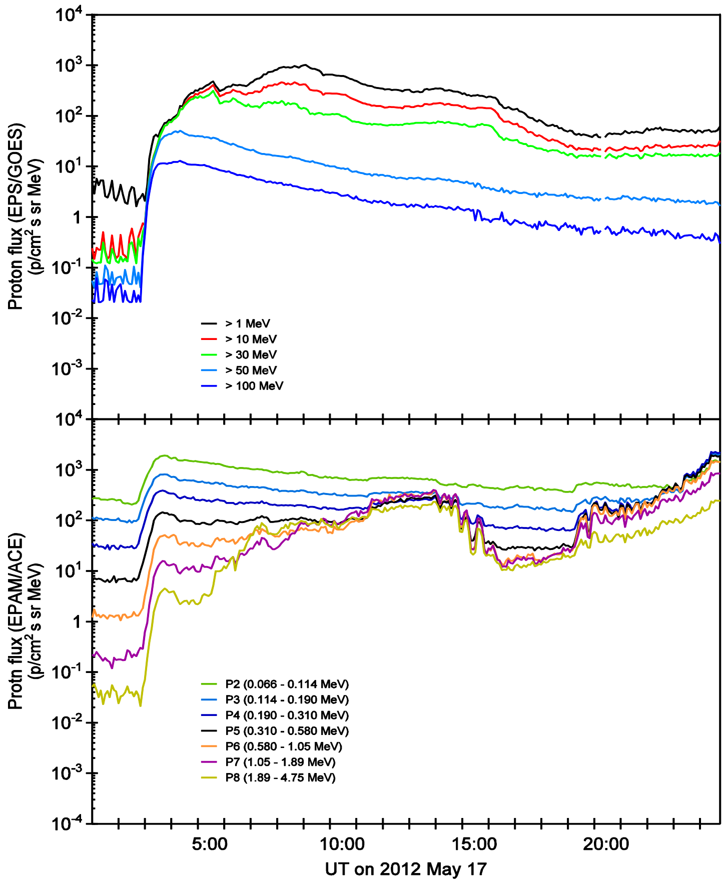
SEP/GLE on 17 May 2012

SEP event-observations associated with energetic particles at 1 AU





Left: two-ribbon **flare** in *SDO*/AIA 1600 Å overlaid with the *RHESSI* HXR sources (from *Li et al., 2013*) on 17 May 2012
Right: **CME** observation by SOHO/LASCO on 17 May 2012
(from http://www.spaceweather.com/)



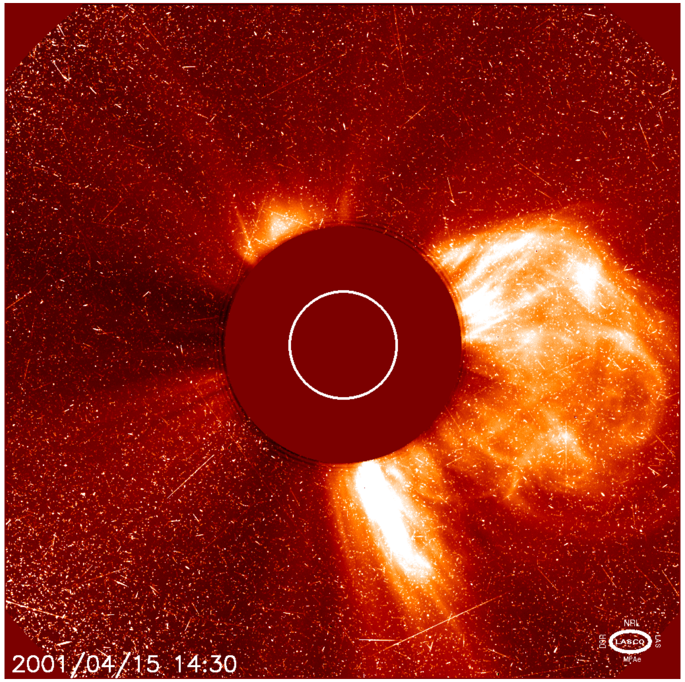
Plainaki et al., ApJ, 2014

- The **SEP event is associated with the M5/1f flare** (peak time on May 17 at 01:47 UT) occurring in the Active Region (AR) 11476, located at N11W76.

- Based on the flare longitude the SEP event was relatively **"well-connected"** to the source region, also considering the observed solar wind speed of ~400 Km/s preceding the event.

SEP/GLE on 15 April 2001

SEP event-observations associated with energetic particles at 1 AU



CME observation by SOHO/LASCO on 15 April 2001
http://soho.nascom.nasa.gov/hotshots/2001_04_15/

- A **strong flare (X14.4/2B)** was observed at the west limb of the solar surface at the position S20W85
- A **fast CME (>1200 km/s)** (*Muraki et al. 2008*; *Gopalswamy et al. 2003*) was associated to the flare.
- Following the detection of gamma and X-rays, the High Energy Proton and Alpha Detector on board **GOES 10 satellite recorded sudden increases in relativistic protons**.

The SEP events as registered at the ground

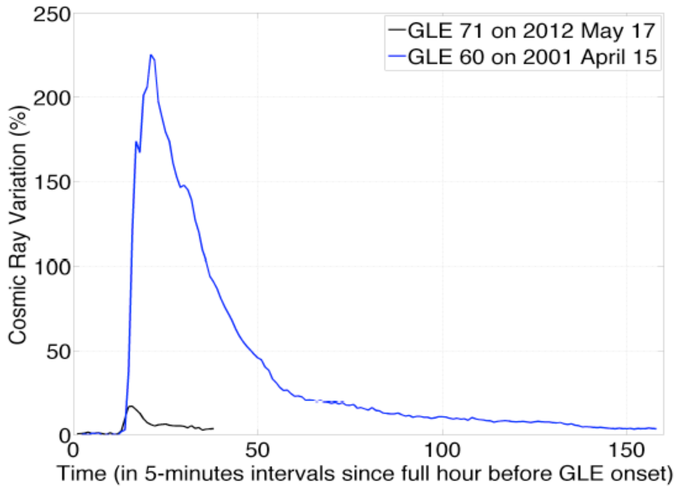
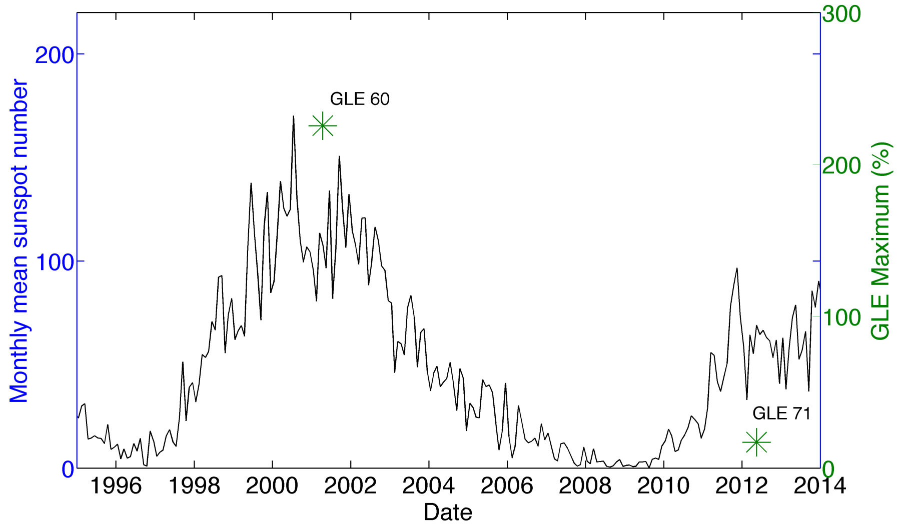


Figure 1: Relative counting rate variation of the South Pole neutron monitor during GLE 60 (in blue) and GLE 71 (in black). The x-axis unit is 5-minutes intervals since the full hour before GLE onset.

Plainaki et al., JPhCS, 2015

GLE 71 and GLE 60 appearance in relation to Solar Activity

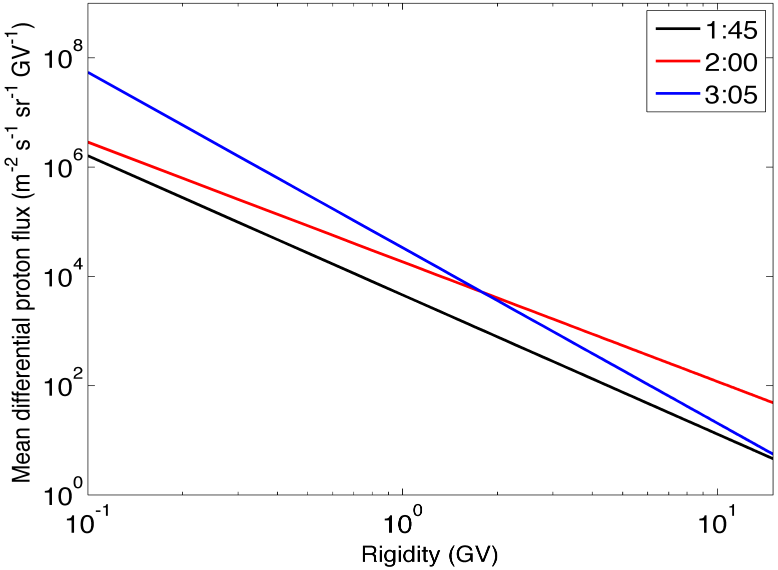


Plainaki et al., ECRS Conference, 2014

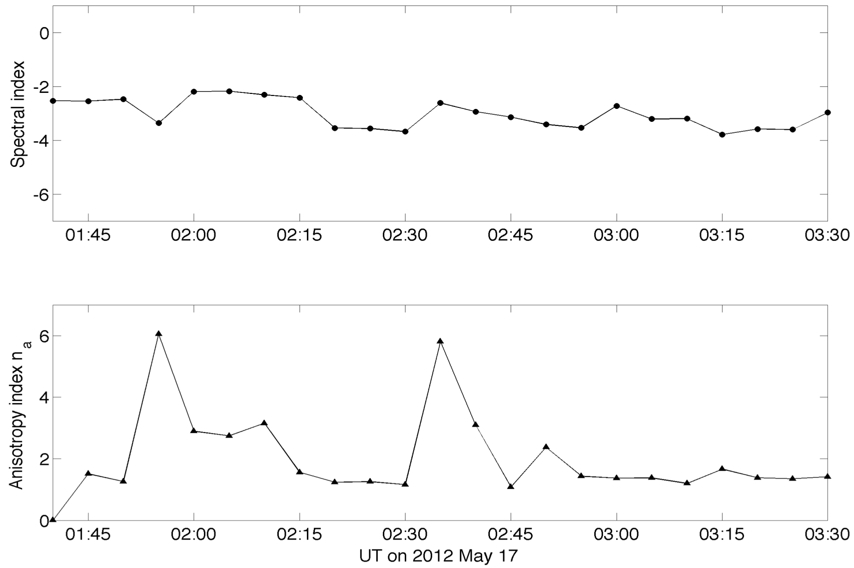
The data were obtained from the NMDB (www.nmdb.eu).

SEP/GLE on 17 May 2012 – Results

SEP spectrum at the top of the atmosphere



Spectral and anisotropy index evolution

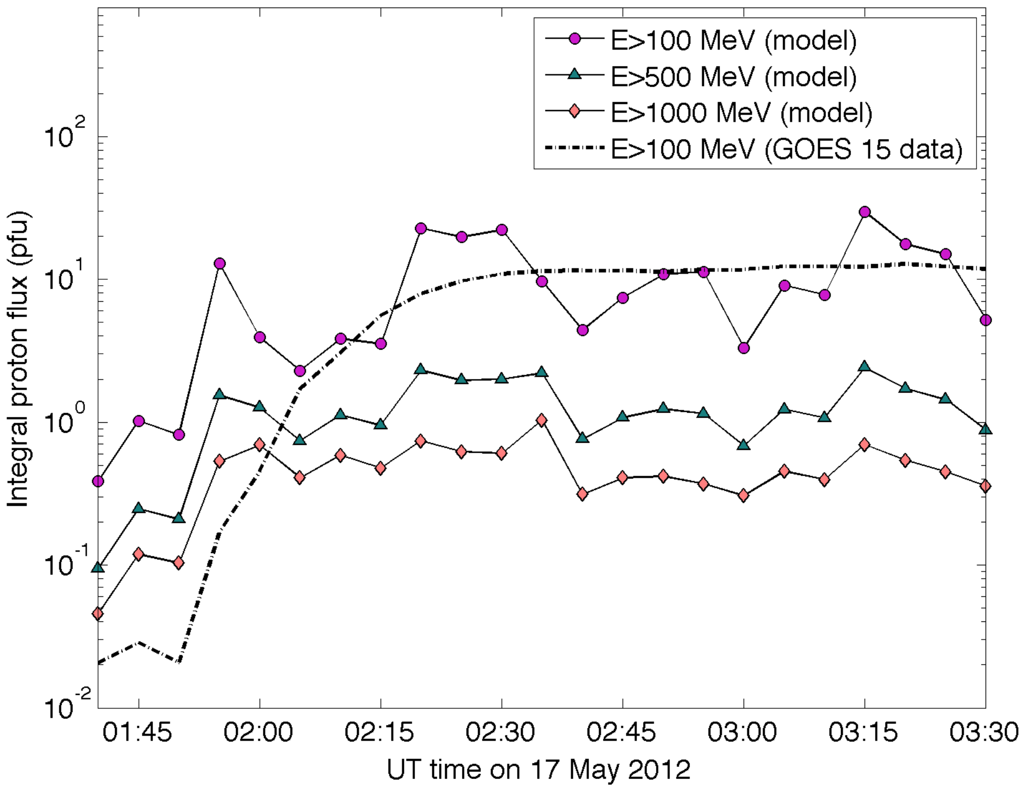


- a **rather soft spectrum** of accelerated protons→ spectral index (in rigidity) varying between -3.8 and -2.1
- the **hardest spectrum is** obtained in the time interval **01:55-02:10 UT→ in good agreement with *Li et al. (2013)* and** consistent with the typical range found by *Ellison and Ramaty (1985)* for **shock wave acceleration**

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.

SEP/GLE on 17 May 2012 – Results

Modeled integral SEP fluxes evolution in comparison with GOES data



Plainaki et al., ApJ, 2014

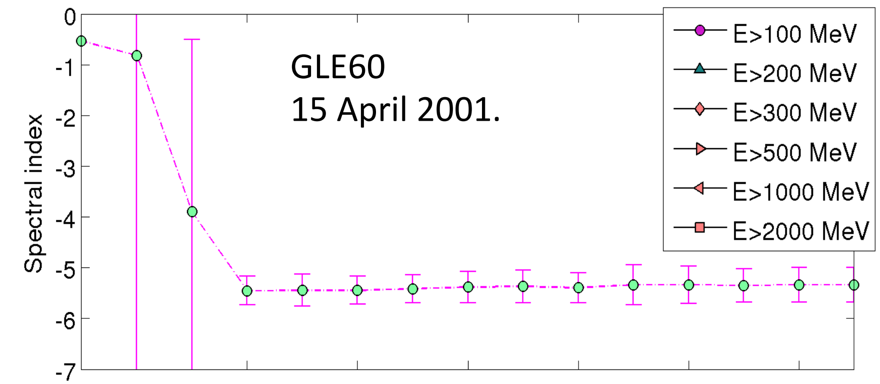
Good agreement between modeled (extrapolated) SEP fluxes and the GOES measurements.
Spatially averaged SEP fluxes are presented here.

Overestimation of the > 100 MeV fluxes in the initial phases of the event.

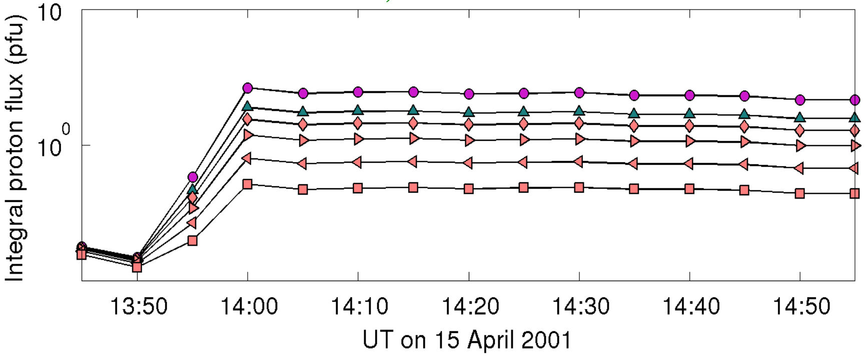
Note that the "streaming limit" effect (*Reames and Ng, 1998*) has not yet been implemented in the model.
Note that a unique, i.e. for the whole energy range, SEP-spectrum has been used.

SEP/GLE on 15 April 2001 – Results

Spectral index evolution

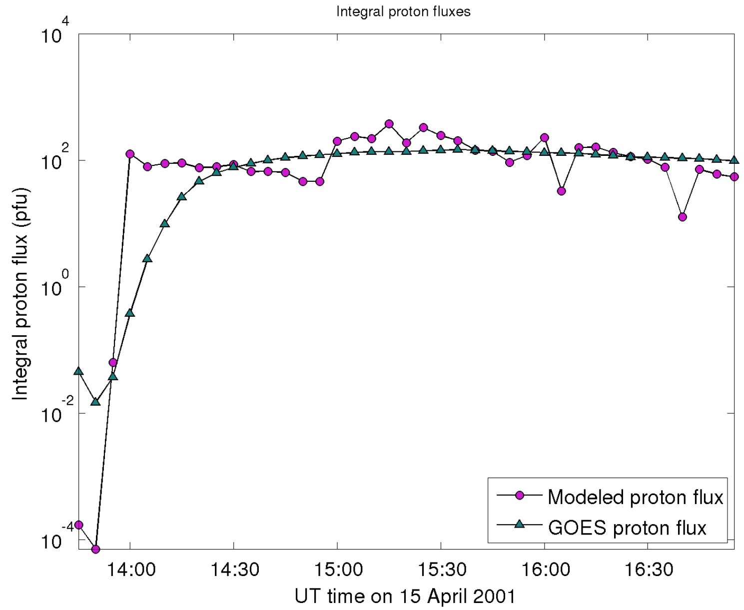


SEP fluxes, at an altitude of ~ 20 km.



Plainaki et al., Sol.Phys., 2010

Modeled and observed SEP fluxes (> 100 MeV), at an altitude of ~ 20 km



Good agreement between modeled (extrapolated) SEP fluxes and the GOES measurements in the main phase.

Need to improve our modeling tools !

Failure of the model to reproduce the initial phase in the low-energy SEP fluxes (using a unique, i.e. for the whole energy range, SEP-spectrum).

Conclusions

Considering the space weather events

- A **hard rigidity spectrum** of accelerated protons was found during the **initial phases** of both events, whereas at later phases, softer spectra were estimated.
- The results for GLE 71 are **consistent with a shock wave acceleration scenario.**
- The model-results can provide realistic estimation of the SEP fluxes in the energy range where NM increases are registered.
- The **integral SEP fluxes** calculated by the model are **in good agreement with GOES observations** if extrapolated to the lower energy range, mostly in the main phase of the event.

In view of space weather monitoring services

Modeling techniques based on ground-level (and space) particle data can provide an alert within 10-20 min for the arrival of the bulk particles of a SEP event.

For a complete monitoring, an interdisciplinary approach is necessary, based on solar photon and particle data.

Discussion and ideas for future applications

1. Space weather monitoring

In the context of space weather monitoring, GLE/SEP modeling can be used in real time for registering the relativistic SEP event evolution. **To do this:** a network of NMs (e.g. Mavromichalaki et al., 2011), providing data **on line,** at least every five min (or more often), is necessary.

http://www.nmdb.eu

NMDB stations

Neutron Monitors participating:
Almaty NM, Kazakhstan (AATB)
Armenian NMs
Athens NM, Greece (ATHN)
Bartol (University of Delaware) NMs
Doi Inthanon, Thailand (PSNM)
Dourbes NM, Belgium (DRBS)
ESOI-TAU, Israel (ESOI)
Guadalajara, Spain (CALM)
Kerguelen (KERG) and Terre Adelie (TERA) stations, France
Kiel, Germany (KIEL, KIEL2)
Koldewey Station, Spitzbergen Lomnicky stit, Slovakia (LMKS)
Oulu, Finland (OULU)
Plateau de Bure NM, France (BURE)
RUSSIAN NMs
Rome, Italy (ROME)
Swiss NMs
Zugspitze, Germany

Discussion and ideas for future applications

1. Space weather monitoring

In the context of space weather monitoring, GLE/SEP modeling can be used in real time for registering the relativistic SEP event evolution. **To do this:** a network of NMs (e.g. Mavromichalaki et al., 2011), providing data **on line,** at least every five min (or more often), is necessary.

Note that in view of future space weather services, satellite particle data can be integrated in the NMBANGLE and NMBANGLE PPOLA models.

NMDB neutron monitor database

http://www.nmdb.eu

Neutron Monitors participating:
Almaty NM, Kazakhstan (AATB)
Armenian NMs
Athens NM, Greece (ATHN)
Bartol (University of Delaware) NMs
Doi Inthanon, Thailand (PSNM)
Dourbes NM, Belgium (DRBS)
ESOI-TAU, Israel (ESOI)
Guadalajara, Spain (CALM)
Kerguelen (KERG) and Terre Adelie (TERA) stations, France
Kiel, Germany (KIEL, KIEL2)
Koldewey Station, Spitzbergen Lomnicky stit, Slovakia (LMKS)
Oulu, Finland (OULU)
Plateau de Bure NM, France (BURE)
RUSSIAN NMs
Rome, Italy (ROME)
Swiss NMs
Zugspitze, Germany

Discussion and ideas for future applications

2. What about SEP events at other planets possessing atmospheres ?

At other planets possessing atmospheres usually only in situ measurements, or observations from orbiters, are available.

A forward modeling technique is necessary in these cases.

An effort to model the interactions of SEPs with the Venusian atmosphere has been been done (Plainaki et al., ANGEO, 2016).

Through modeling of SEP-atmosphere interactions important information on the ionization and the dependence of its rate and profile (with altitude) can be obtained. Such information has an interdisciplinary value since it can be used as a feedback for atmospheric chemistry studies and cloud formation investigations at different planets (e.g. at Venus, see Nordheim et al., 2015).

Venus could be the next to target for investigating the role of space weather.

Thank you for your attention

Acknowledgements

We acknowledge the NMDB database (www.nmdb.eu), founded under the European Union's FP7 programme (contract no. 213007) for providing data.
We also acknowledge all neutron monitor teams: Alma Ata, Apatity, Athens, Baksan, Emilio Sergè Observatory,Fort Smith, Inuvik, Irkutsk, Irkutsk 2, Irkutsk 3, Jungfraujoch, Jungfraujoch-1, Kerguelen, Kiel, Lomnicky Stit, Magadan, McMurdo, Moscow, Nain, Norilsk, Newark, Oulu, Peawanuck, Rome, South Pole, Terre Adelie, Thule, Tixie Bay, and Yakutsk.

Literature

Belov, A. V. et al., 2005, AnGeo, 23, 2281

Bombardieri, D. J. et al. 2007, ApJ, 665, 813

Dorman, L. I. 2004, Astrophysics and Space Science Library, Vol. 303 (Dordrecht: Kluwer)

Gopalswamy, N. et al., 2013, ApJL, 765, L30

Lee, M. A., Mewaldt, R. A., & Giacalone, J. 2013, SSRv, 173, 247

Liu, C., et al. 2009, ApJ, 703, 757

Mavromichalaki et al., AdSR, 47, 12, 2210-2222

Nordheim, T. A. et al., 2015, Icarus, 245, 80–86.

Plainaki et al., ANGEO, 2016, Ann. Geophys., 34, 595–608.

Plainaki et al., 2016, J. Space Weather Space Clim., vol. 6, A31

Plainaki et al., 2014, ApJ, 785(2), art. id. 160

Plainaki et al., 2010, Solar Physics, 264 (1), pp.239-254

Plainaki et al., 2007, JGR (Space Physics), vol. 112, p. 4102

Reames, D. V. 1999, SSRv, 90, 413

Shea, M. A., & Smart, D. F. 1982, SSRv, 32, 251

Tylka, A.J. and M. A. Lee, 2006, ApJ 646, 1319

Zurbuchen, T., & Richardson, I. G. 2006, SSRv, 123, 31.