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THE TIME PROFILE OF RELATIVISTIC SOLAR PARTICLE EVENTS – A PREDICTION TOOL IN RADIATION ADVISORIES FOR CIVIL AVIATION?

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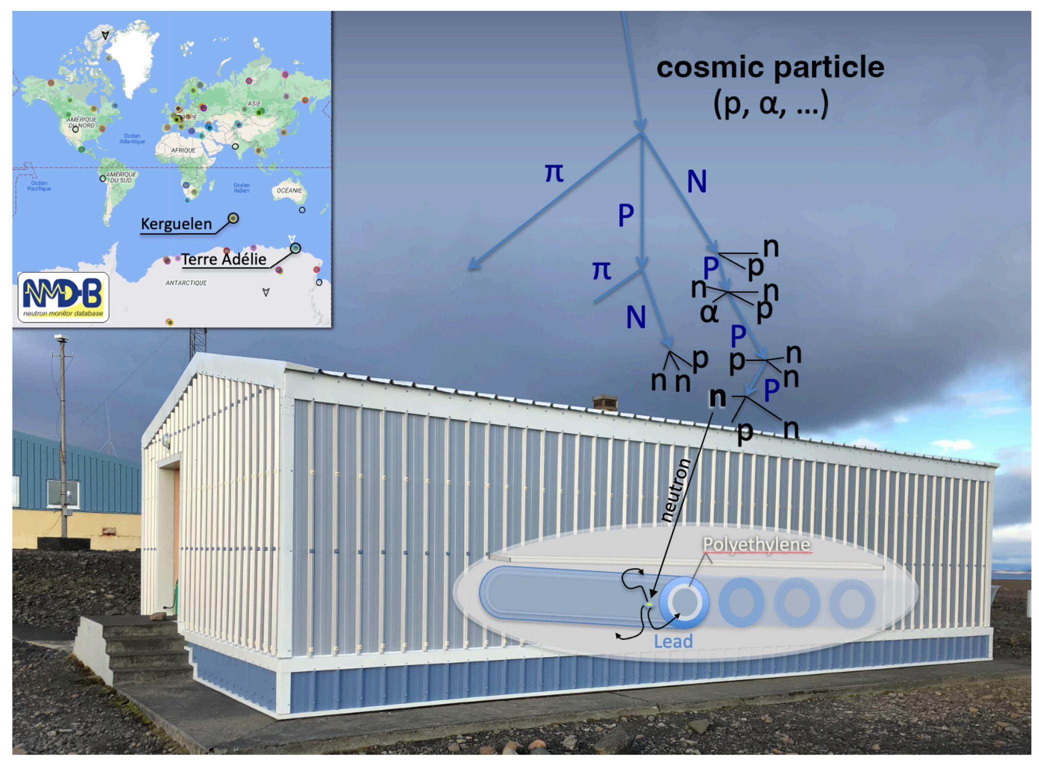
Abstract The most energetic particles accelerated in solar eruptive events are protons and nuclei with energies that may reach a few tens of GeV. They can be detected on the Earth through the secondaries they produce when interacting with the atmosphere. Solar energetic particle events where this happens are called Ground-Level Enhancements (GLEs). The secondary particles constitute a source of radiation in the atmosphere that may temporarily exceed the permanent dose rate from galactic cosmic rays. This makes the monitoring of radiation doses received by aircrew from GLEs one issue of space weather services for civil aviation. This study addresses the time profiles of GLEs, in the search for commonalities that can be used to constrain models of acceleration and propagation and to forecast the evolution of an ongoing event.

We investigate historical GLEs (1971–2012) with the worldwide network of neutron monitors, comparing the rise and the decay as observed by the neutron monitor with the strongest response. We evaluate statistical correlations between rise times and decay times and compute a normalised median GLE time profile. An empirical correlation reported in earlier work between the observed rise times and decay times of the neutron monitor count rate profiles is confirmed. We show that the observed time profiles are in general close to the median one, while deviations from the median time profile can be attributed to the detection of particles that are reflected at a magnetic mirror beyond Earth orbit, due to a previous CME. We discuss the usefulness of our results for the prediction of the duration of an ongoing GLE and dose rates at aviation altitudes.

1) *Cosmic ray observations with neutron monitors (e.g., Buetikofer 2018)*

a) Atmospheric cascade:
- Primary cosmic ray (proton, nucleus > 430 MeV/nuc) impacting the Earth's atmosphere
- Nuclear reactions: secondary protons, neutrons, …
- Pursuit … ground level

b) Neutron monitor:
- Counter tubes surrounded by Pb-rings (neutron production)
- Nuclear reaction in counter tube: n + $^{10}_{5}$B -> $^{7}_{3}$Li + α
- Ionisation of the gas, detection
- Worldwide network => energy spectrum and angular distribution of the primary particles



2) *Solar energetic particles: GLEs*

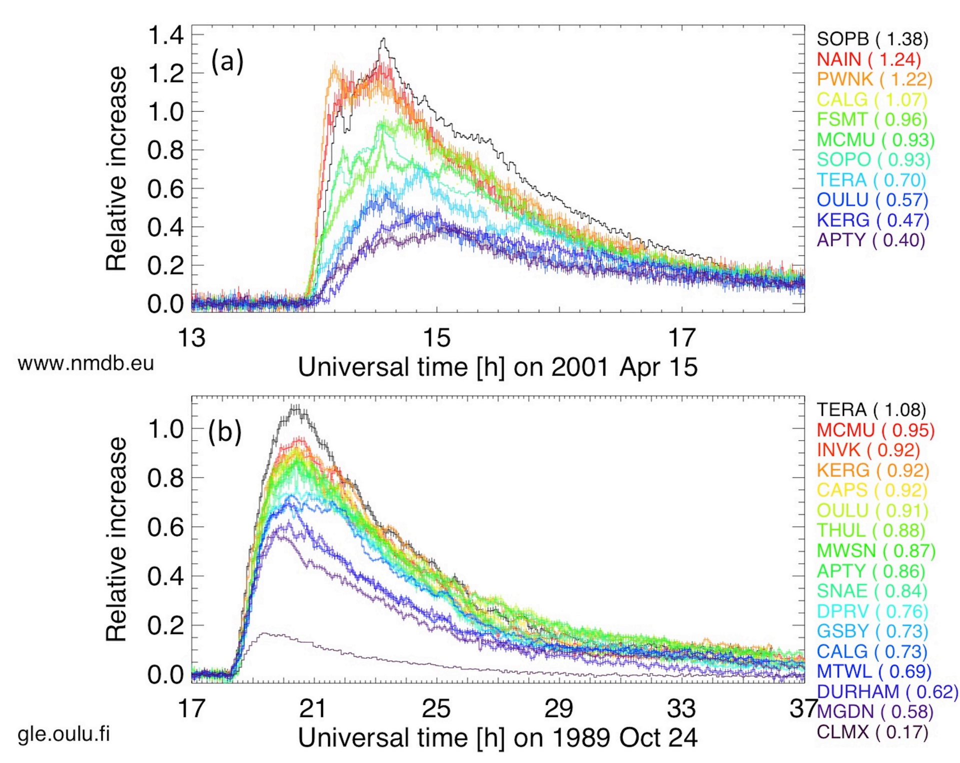
- Sporadic contribution, several hours duration: *Ground-Level Enhancement* (GLE)
- Rare events (73 since 1942)

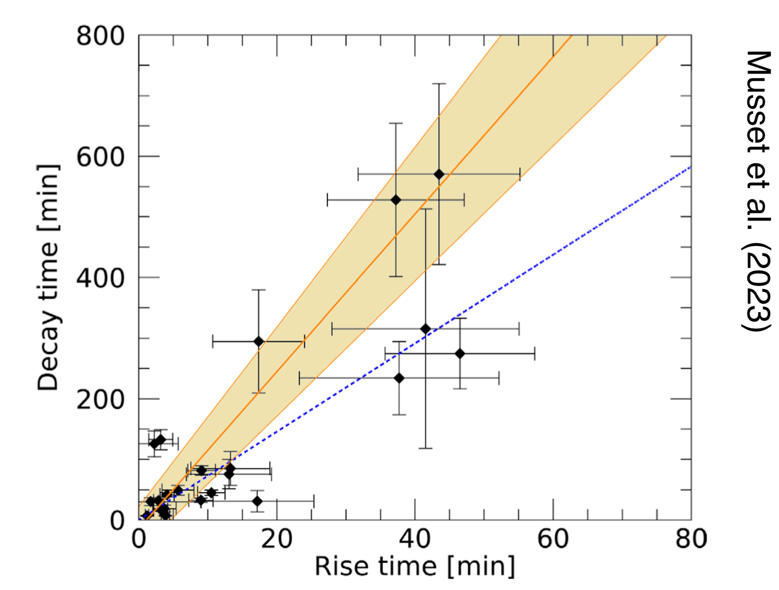
2) *Time profiles of GLEs*

Typical time profile: fast rise – slow decay

Two illustrations: GLEs 2001 Apr 15 and 1989 Oct 24
- Different colours: different neutron monitors at high latitudes (different arrival directions of incoming nucleons)
- Slow rise, rapid decay
- Note: similar time profiles, but different time scales in the two plots (5 h vs. 20 h)

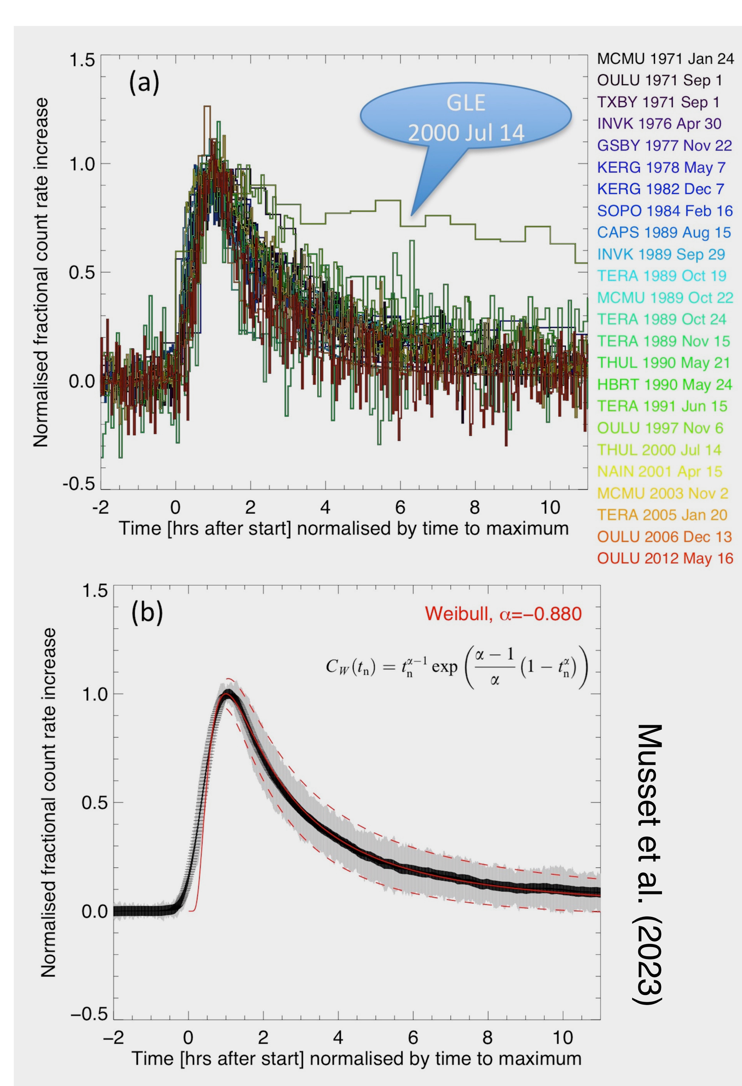
Hints towards a relationship between rise time and decay time: Moraal et al. (2015), Strauss et al. (2017), Musset et al. (2023)- but broad scatter





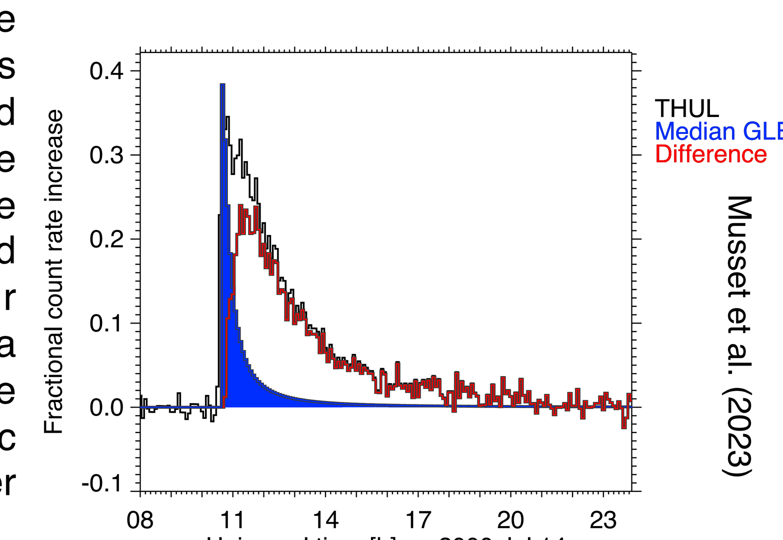
3) *A normalised time profile of GLEs*

- Consider the neutron monitor where the GLE has the highest amplitude (particles coming along the interplanetary magnetic field)
- Normalise the amplitude of the GLE (excess above pre-event background, corrected to sea level) to the maximum in 5 minute-integrated records
- Normalise the time t to $t_n = (t - t_{start}) / t_{rise}$ (t_{rise}=time from start to peak)
- Same procedure for all GLEs >10% above background since 1971 (23 GLEs)
- Plot (Fig. a): scatter around well-defined median time profile, 1 outlier (2000 Jul 14)
- Median profile (Fig. b) with mean absolute deviation (grey shading) and fit of the decay by a simple mathematical function (red solid line; Weibull function C_W)



The outlier: statistical or physical explanation?

- 2000 Jul 14 GLE - a counter-example to the claimed similarity of GLE time profiles? Or an additional particle source?
- Bieber et al. (2002) model the angular distribution of the incoming particles during this GLE => particles reflected at a magnetic mirror at about 1.3 AU (CME passing Earth on Jul 13) start to be detected between 10:35 and 11 UT
- Agreement with the start of excess emission (red curve) above the median GLE time profile (blue-shaded curve) => outlier because of a physical difference (strong magnetic mirroring) with other GLEs



Summary and conclusion:

- The time profiles of GLEs show a correlation between rise time and decay time that allows for the definition of a median GLE time profile (normalised amplitude, normalised time).
- Deviations from the median (1 outlier) can be explained by an additional particle source (back streaming particles from a magnetic mirror beyond 1 AU).
- Interpretation: Particle transport in the IP medium (Strauss et al. 2015)? Solar processes (Musset et al. 2023)?
- Possible space weather application: estimation of the duration of an ongoing GLE, once the GLE peak has been observed:
  - Scale the median time profile (or the decay described by the Weibull function) to the GLE in progress (amplitude, time)
  - Uncertainty: how to estimate the probability of back streaming particles from a magnetic mirror beyond 1 AU?
  - Potentially useful for the ICAO space weather service (duration of a radiation advisory)

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