Ground Level Enhancement Events: Interplanetary Protons versus Protons Interacting at the Sun.

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Abstract

We compare results of the solar high-energy proton detection with the neutron monitor network in Ground Level Enhancement (GLE) events and the data of pion-decay gamma-ray emission produced by high-energy protons interacting at the Sun. Observational data support the idea of a common origin of the GLE-producing protons and the protons interacting at the Sun to produce sustained gamma-ray emission. Then we discuss capabilities of the CME bow-shock acceleration models to explain the observational data and argue for the flare and CME synergy in production of high-energy protons in the long duration events.

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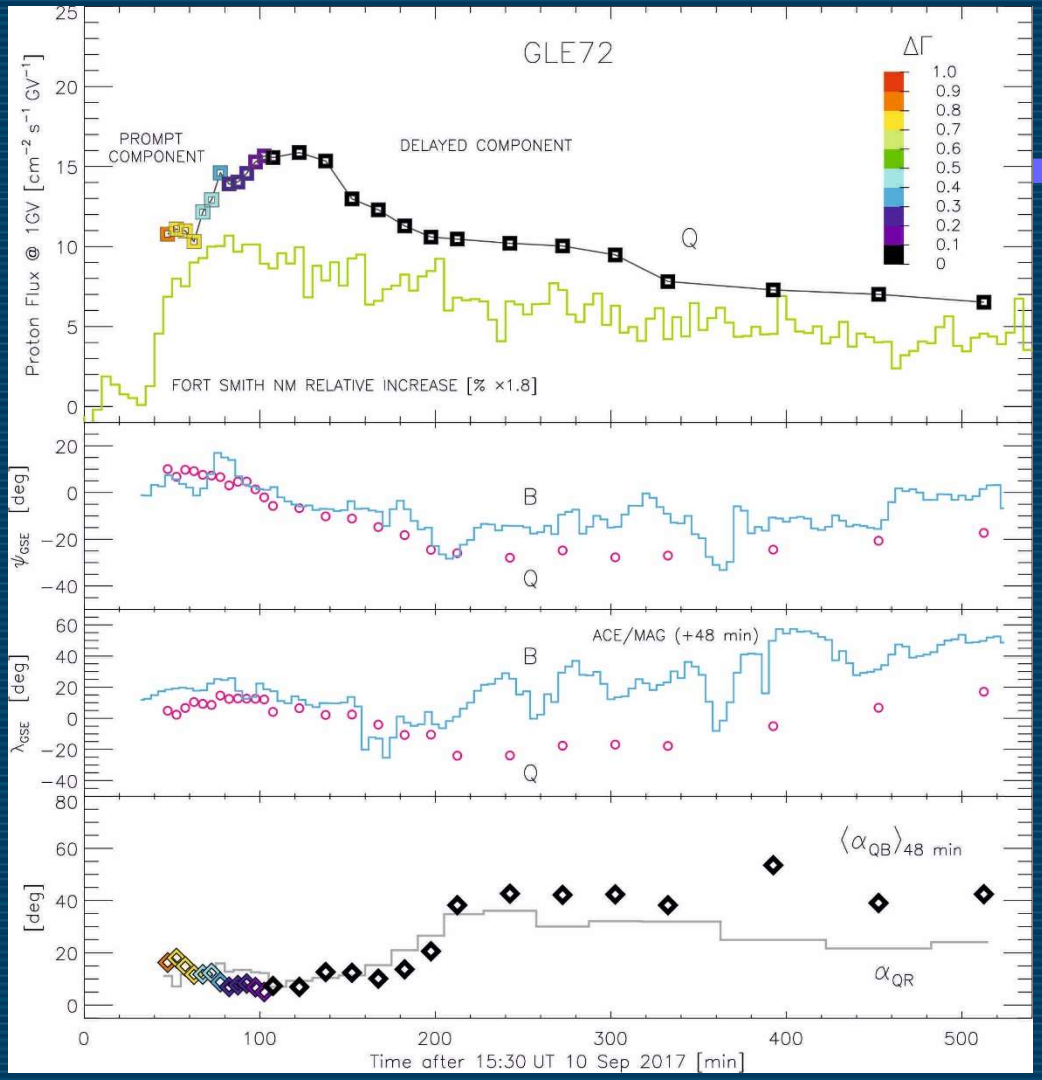
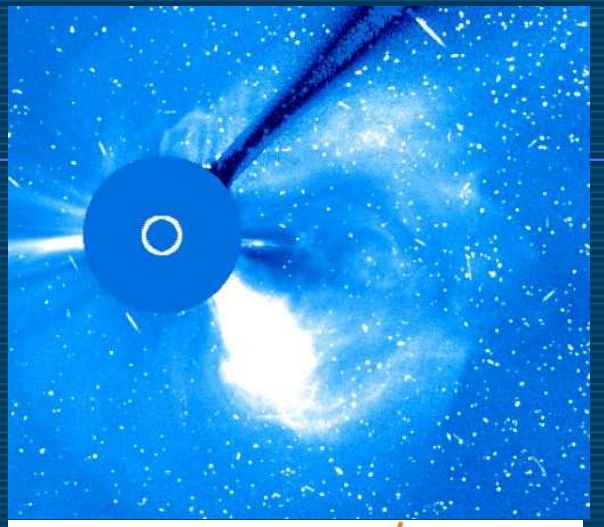
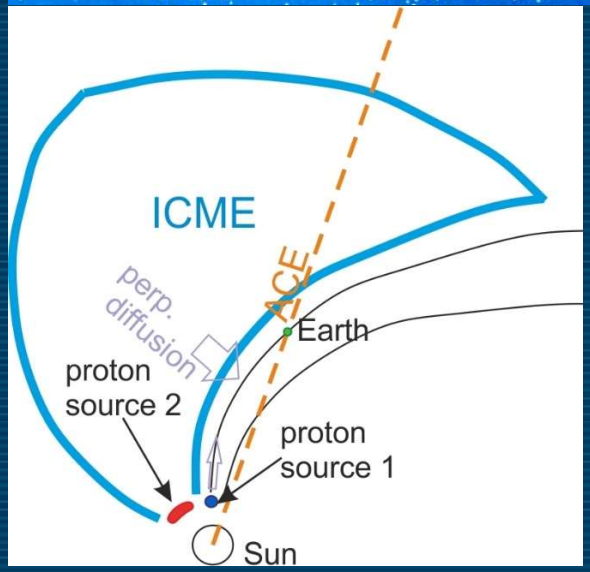
GLE database: http://gle.oulu.fi

The 10 September 2017 GLE event (GLE72)

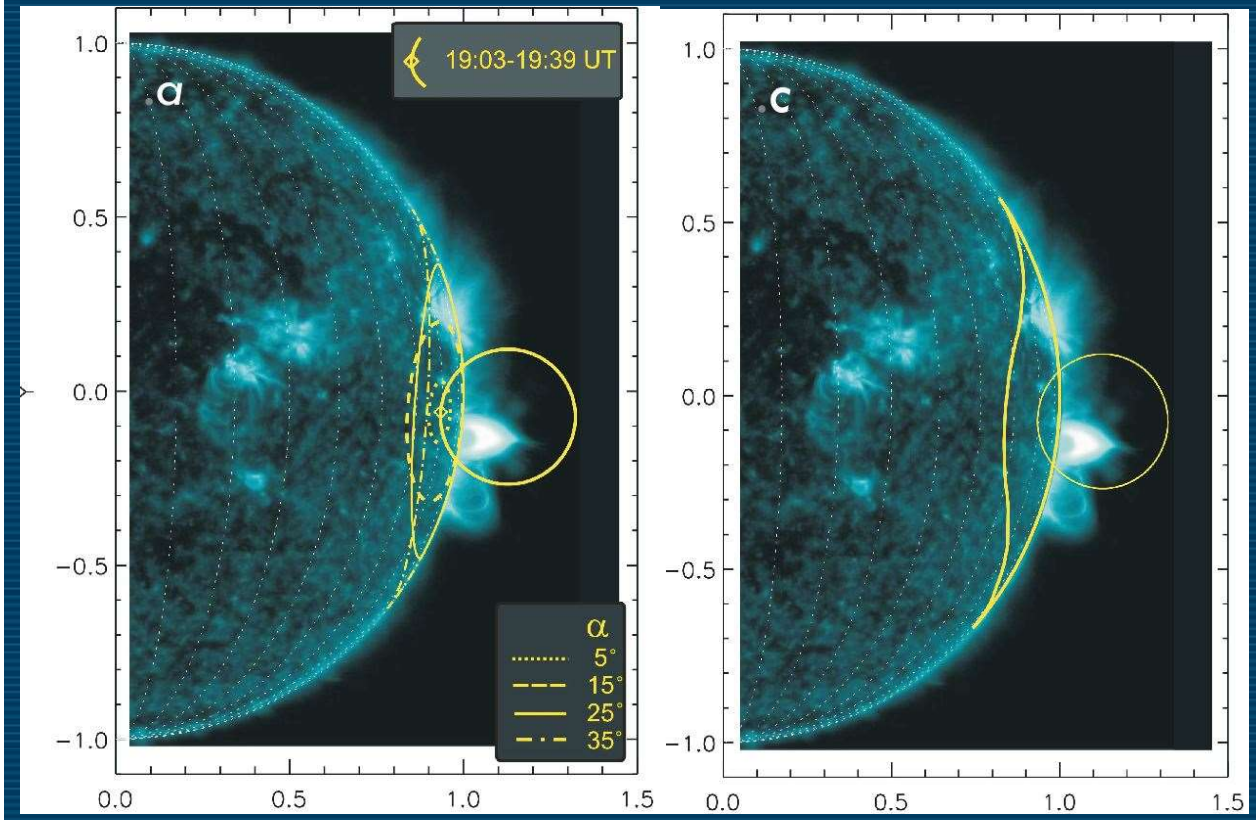






Mishev et al., 2018, Solar Phys., 293, 136
Kocharov et al., 2020, Astrophys. J., 890, 13.

Solar sources of high-energy gamma-ray emission observed with Fermi-LAT on 10 September 2017



Omodei et al 2018 ApJL 865 L7

Ajello et al 2021 ApJS 252 13

Kocharov et al 2021 ApJ 915 12

CORE PLUS HALO MODEL OF DIFFUSIVE SHOCK ACCELERATION AND STOCHASTIC RE-ACCELERATION

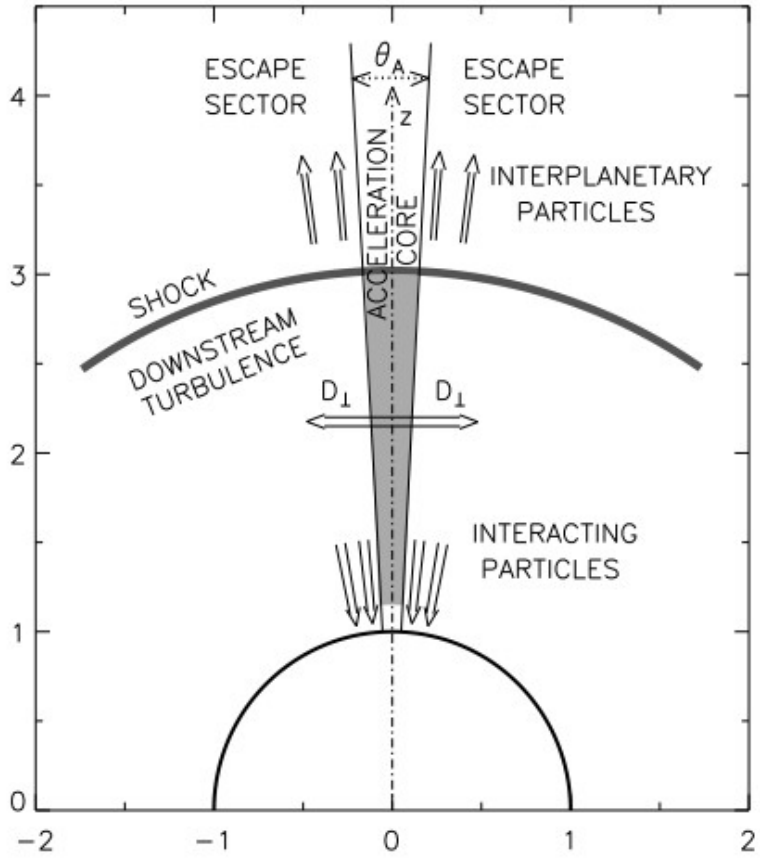
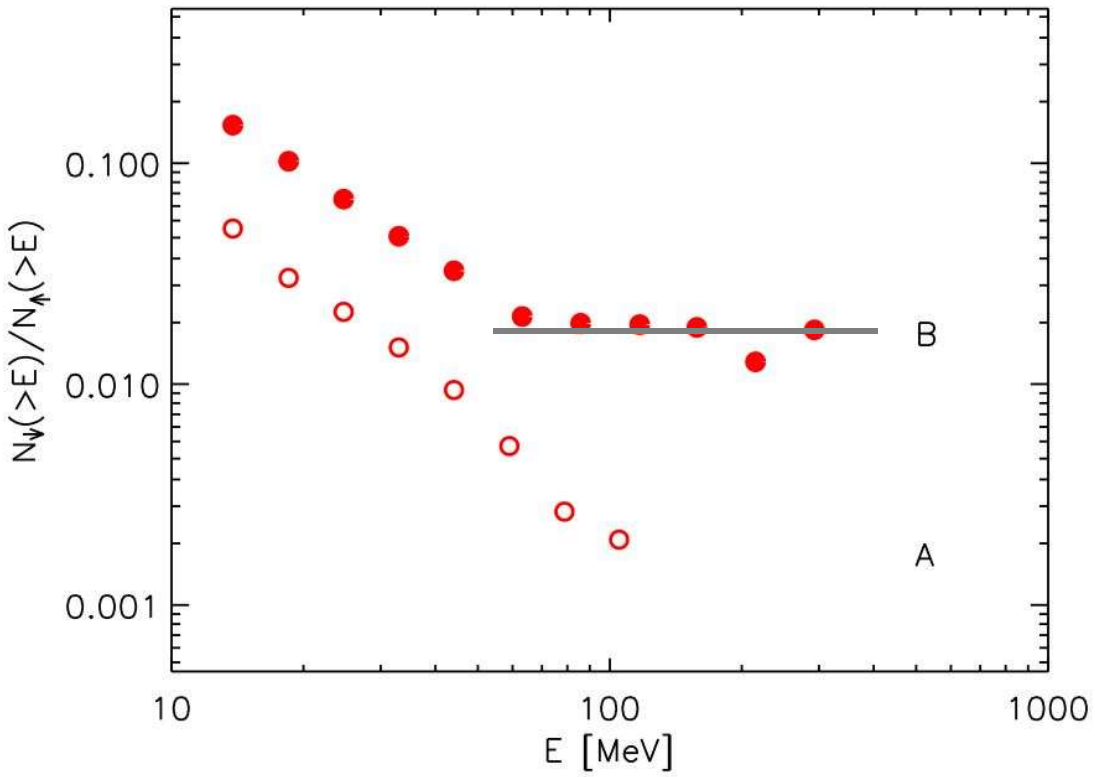


Fig. 1.— Particle acceleration and transport model. Shaded is the region of stochastic re-acceleration of the shock accelerated particles. Effective depth of this region is consistent with the proton energy spectrum and hence depends on the energy of resonant protons.

$D_{HALO}/D_{CORE}=50$,
$D_{1,CORE}(0.1\ MeV)=2*10^6$ km^2/s

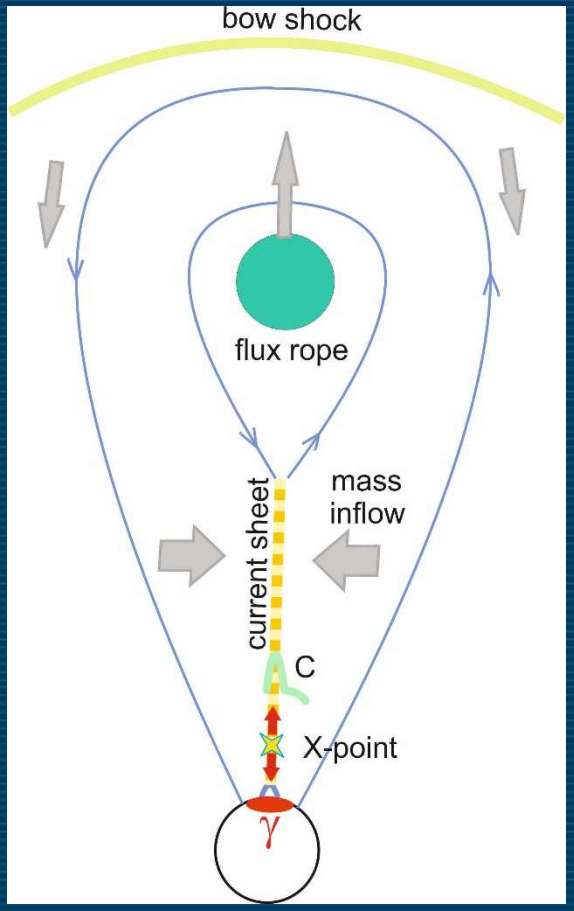
L. Kocharov, T. Laitinen, A. Afanasiev, R. Vainio, K. Mursula, and J.M. Ryan (2015) ApJ, 806, 80

Interacting protons vs Interplanetary protons from the shock acceleration modeling



Number ratio of interacting protons to interplanetary protons with energy $\geq E$ for the modeled cases A and B (irregularities are due statistical limitations).

Possible sources of high-energy proton acceleration after the flare impulsive phase



- Schematic showing the locus of possible high-energy gamma-ray sources, situated beneath the CME-trailing current sheet with a reconnection point (X), from where the bidirectional outflows originate, and the secondary ejection (C).

Summary

- We have compared results of the solar high-energy proton detection with neutron monitor network in Ground Level Enhancement (GLE) events and the data of pion-decay gamma-ray emission produced by high-energy protons interacting at the Sun. Observational data support the idea of a common origin of the GLE-producing protons and the protons interacting at the Sun to produce sustained gamma-ray emission. We discuss capabilities of the CME bow-shock acceleration models to explain the observational data and argue for the flare and CME synergy in production of high-energy protons in the long duration events.