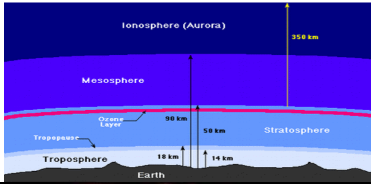
Objective: Universe at high energies

Acceleration, propagation of high energy particles,
Extreme conditions may require new physics ...

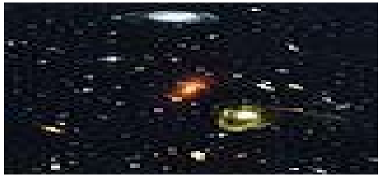
1. Acceleration in atmospheric electric field
   Energy ~1 GeV Scale ~10^5-10^6 cm

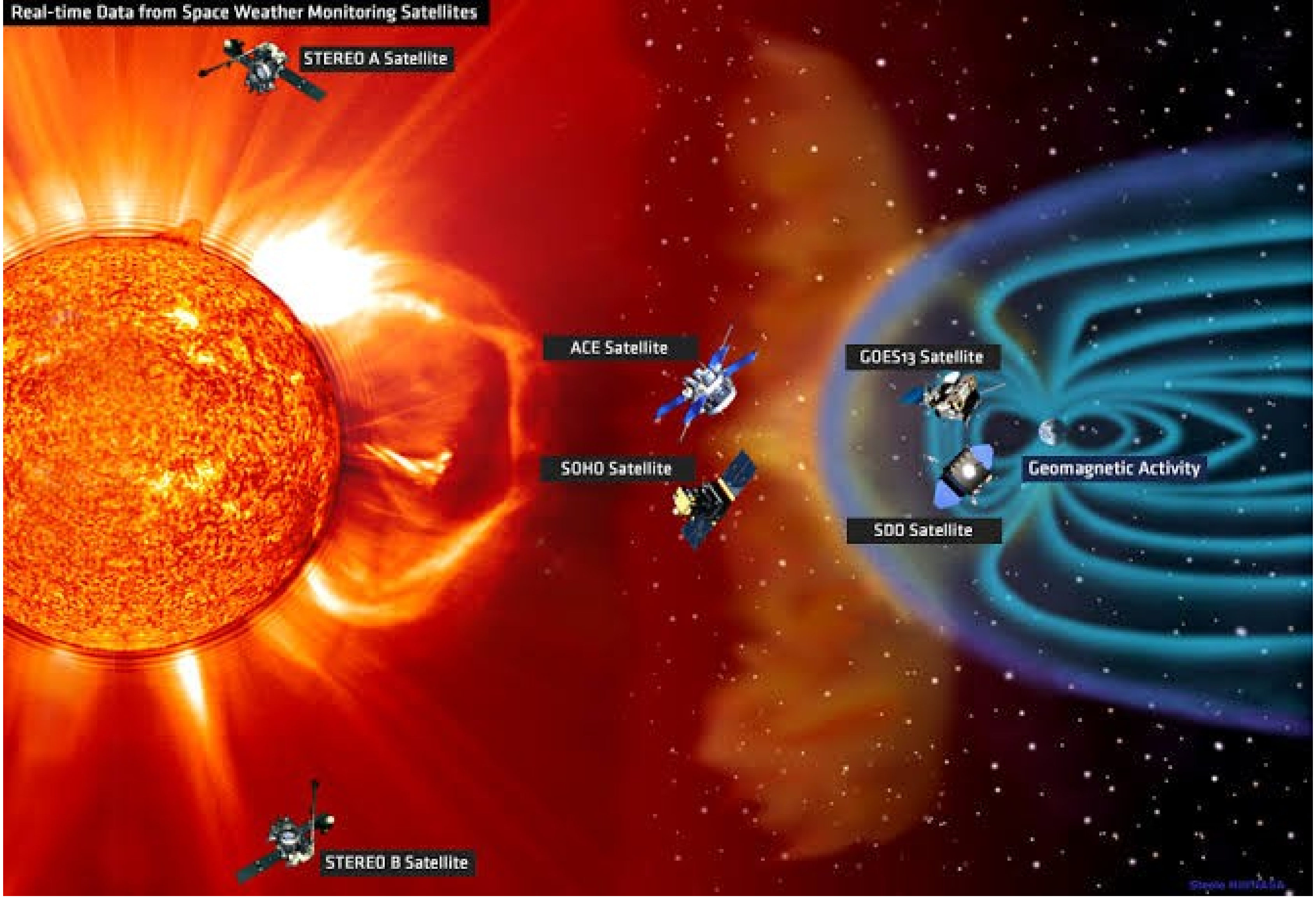


2. Solar storms, Coronal Mass Ejections
   Energy ~10 GeV Scale ~10^{11}-10^{13} cm

3. Galactic Cosmic Rays at " Knee "
   Energy ~10^6 GeV Scale ~10^{21}-10^{23} cm

4. Diffuse multi-TeV **γ**-rays
   Energy ~10^{11} GeV Scale ~10^{24}-10^{26} cm

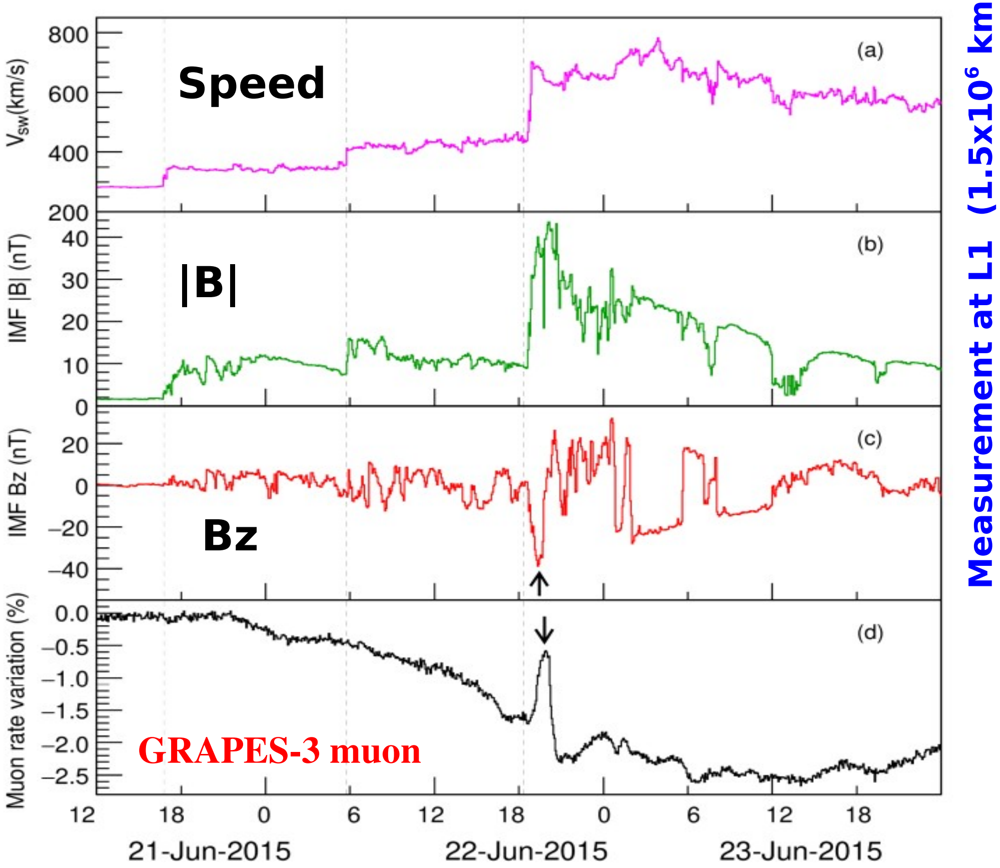



Real-time Data from Space Weather Monitoring Satellites
STEREO A Satellite
ACE Satellite
SOHO Satellite
GOES13 Satellite
Geomagnetic Activity
SDO Satellite
STEREO B Satellite

Transient weakening of Earth's magnetic shield probed by a cosmic ray burst

Physical Review Letters 117 (2016) 171101, P.K. Mohanty et al.

22 June 2015

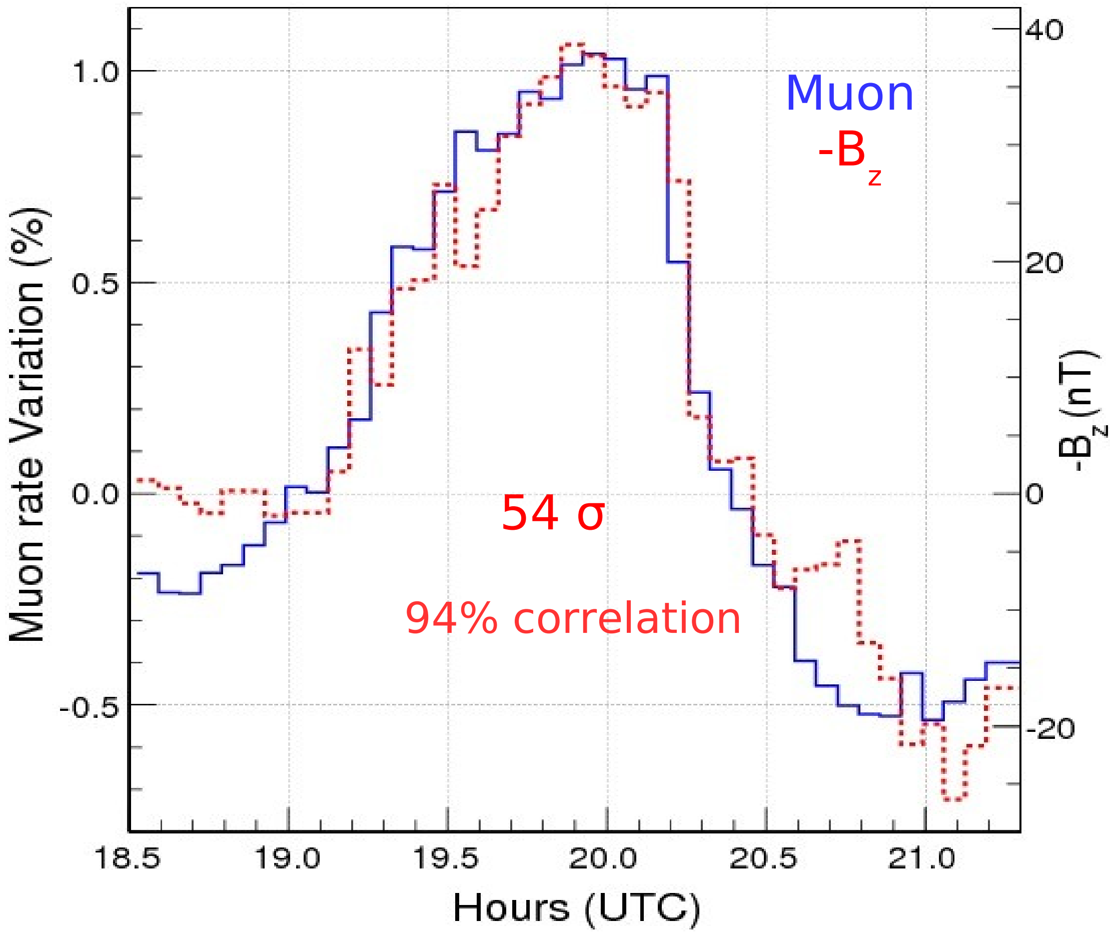


On 22 June 2015 a massive solar storm occurred (Coronal Ejection)

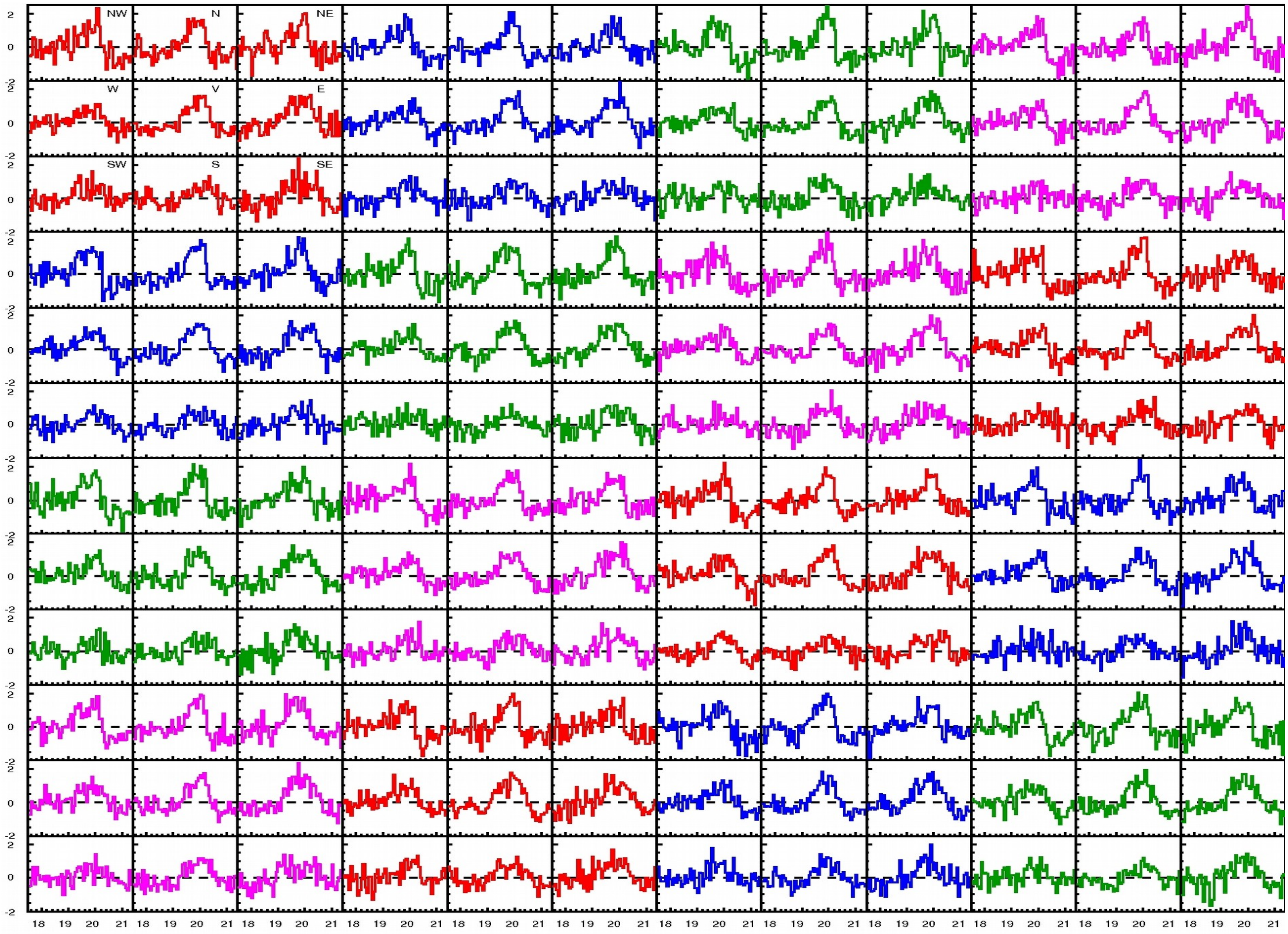
Mass=10^{10} tonne
Energy=10^{33} erg
Solar power= 4×10^{33} erg/s

Initial Speed= 1400 km/s
Speed at L1=700 km/s

22 June 2015 Ooty, midnight

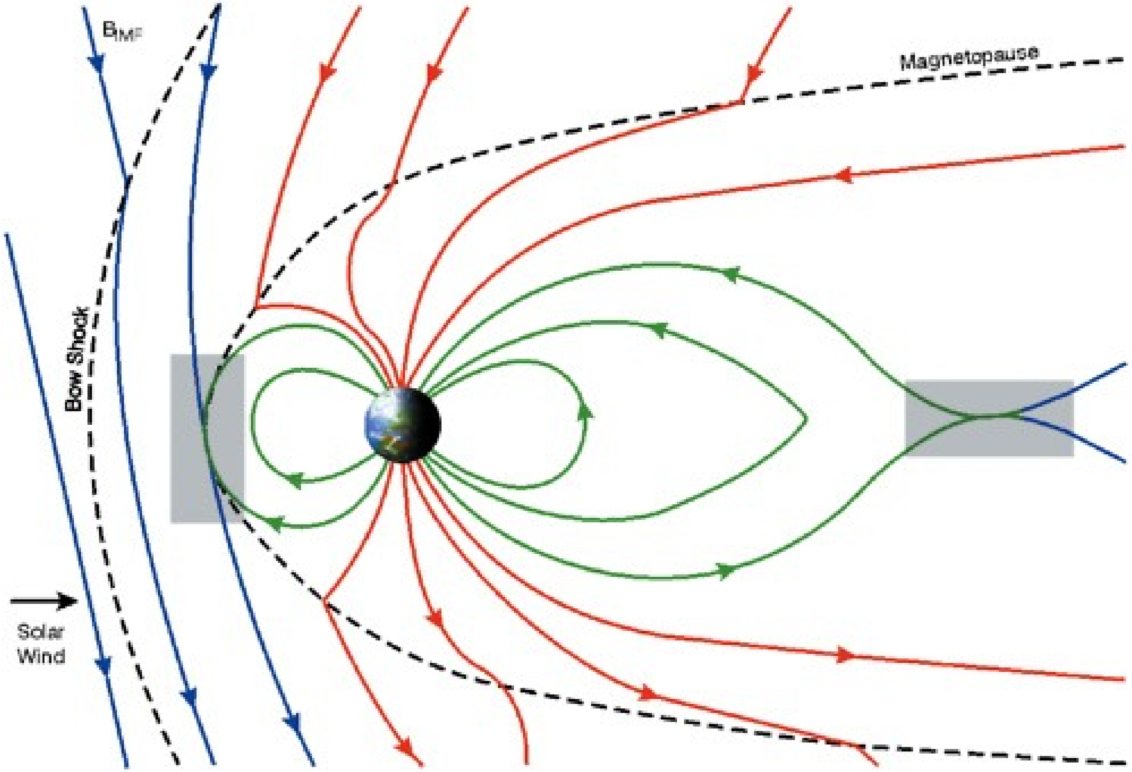


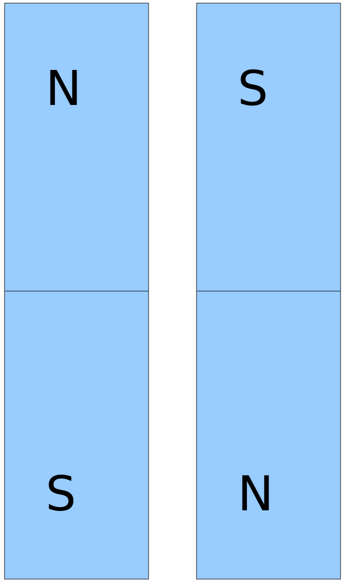
10^6 excess on a background of $3\text{x}10^8$ muons



>5σ	42
4-5σ	37
3-4σ	40
<3σ	25

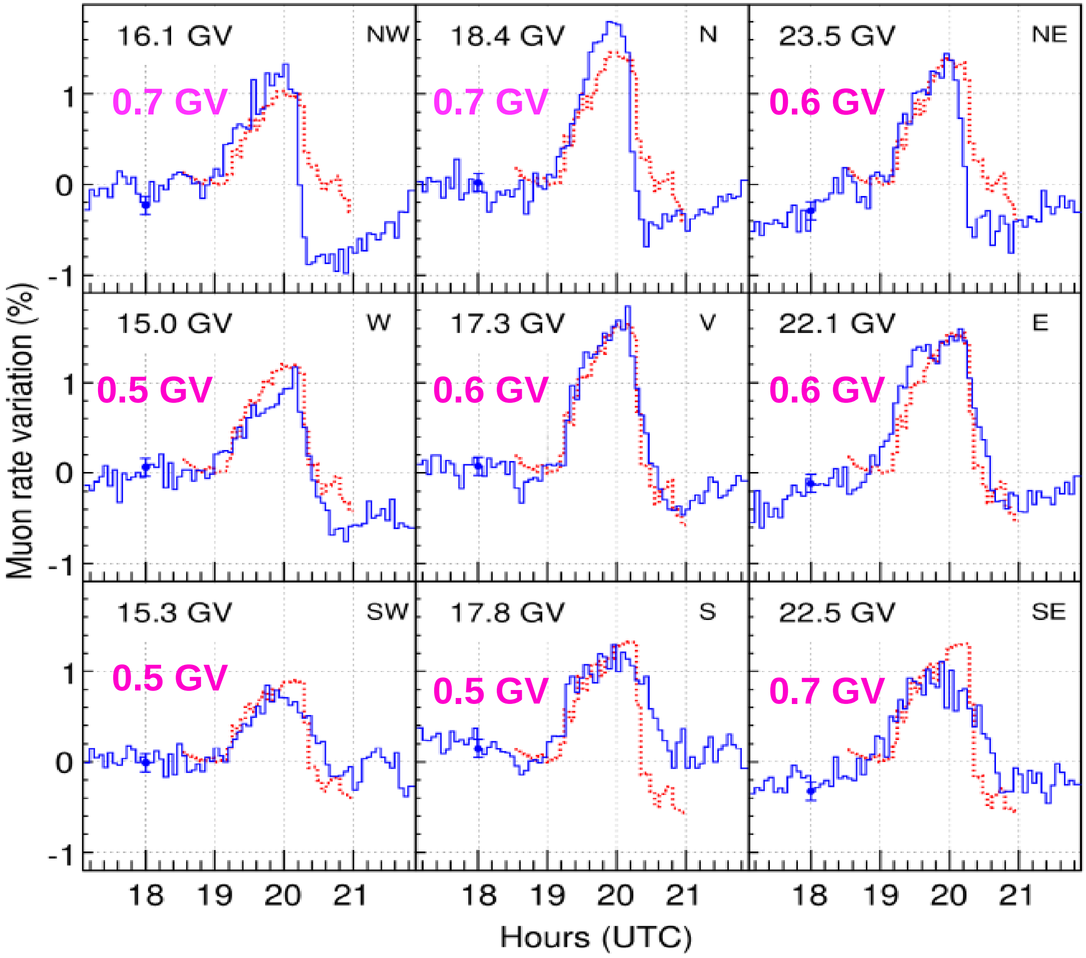
Magnetic Reconnection





Magnetic reconnection results opening of earth's magnetic field lines allowing solar plasma to flow into earth's atmosphere triggering geomagnetic storms

Reproduction of the burst



Data
Simulation

Results

91% correlation

Cutoff rigidity became lower by 0.5 – 0.7 GV

Geomagnetic field weakened by 680nT

http://www.sciencemag.org/news/2016/07/here-s-how-world-could-end-and-what-we-can-do-about-it

Here's how the world could end—and what we can do about it

sciencemag.org/news/2016/07/here-s-how-world-could-end-and-what-we-can-do-about-it

08/07/2016

Threat one: Solar storms

CMEs don't harm human beings directly, and their effects can be spectacular. By funneling charged particles into Earth's magnetic field, they can trigger geomagnetic storms that ignite dazzling auroral displays. But those storms can also induce dangerous electrical currents in long-distance power lines. The currents last only a few minutes, but they can take out electrical grids by destroying high-voltage transformers—particularly at high latitudes, where Earth's magnetic field lines converge as they arc toward the surface.

Threat two: Cosmic collisions

For another menace from the sky—an impact by a large asteroid or comet—there is no way to limit the damage. The only way for humanity to protect itself, researchers say, is to prevent the collision altogether.

Threat three: Supervolcanoes

The most inexorable threat to our modern civilization, however, is homegrown—and it strikes much more often than big cosmic impacts do. Every 100,000 years or so, somewhere on Earth, a caldera up to 50 kilometers in diameter collapses and violently expels heaps of accumulated magma. The resulting supervolcano is both unstoppable and ferociously destructive. One such monster, the massive eruption of Mount Toba in Indonesia 74,000 years ago, may have wiped out most humans on Earth, causing a genetic bottleneck still apparent in our DNA—although the idea is controversial.

What would happen if another carrington-like event of 1857 September 1-2 occur today?

Earth missed one on July 2012

whitehouse.gov/the-press-office/2016/10/13/executive-order-coordinating-efforts-prepare-nation-space-weather-events

EXECUTIVE ORDER 13-October-2016

COORDINATING EFFORTS TO PREPARE THE NATION FOR SPACE WEATHER EVENTS

By the authority vested in me as President by the Constitution and the laws of the United States of America, and to prepare the Nation for space weather events, it is hereby ordered as follows:

Section 1. Policy. Space weather events, in the form of solar flares, solar energetic particles, and geomagnetic disturbances, occur regularly, some with measurable effects on critical infrastructure systems and technologies, such as the Global Positioning System (GPS), satellite operations and communication, aviation, and the electrical power grid. Extreme space weather events -- those that could significantly degrade critical infrastructure -- could disable large portions of the electrical power grid, resulting in cascading failures that would affect key services such as water supply, healthcare, and transportation. Space weather has the potential to simultaneously affect and disrupt health and safety across entire continents. Successfully preparing for space weather events is an all-of-nation endeavor that requires partnerships across governments, emergency managers, academia, the media, the insurance industry, non-profits, and the private sector.

Transient Weakening of Earth's Magnetic Shield Probed by a Cosmic Ray Burst

P. K. Mohanty, K. P. Arunbabu, T. Aziz, S. R. Dugad, S. K. Gupta,*
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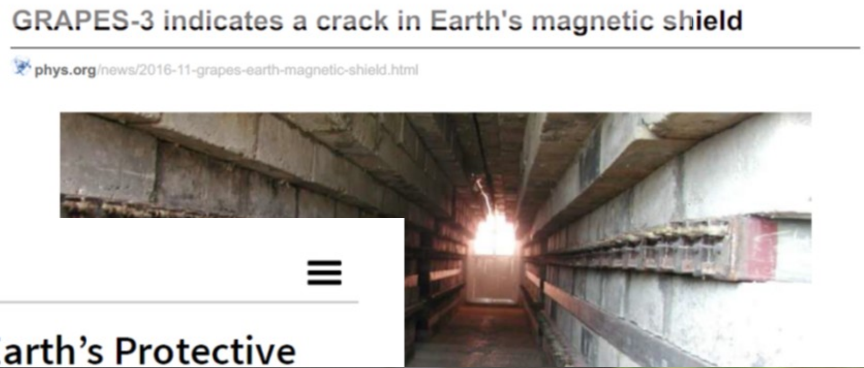
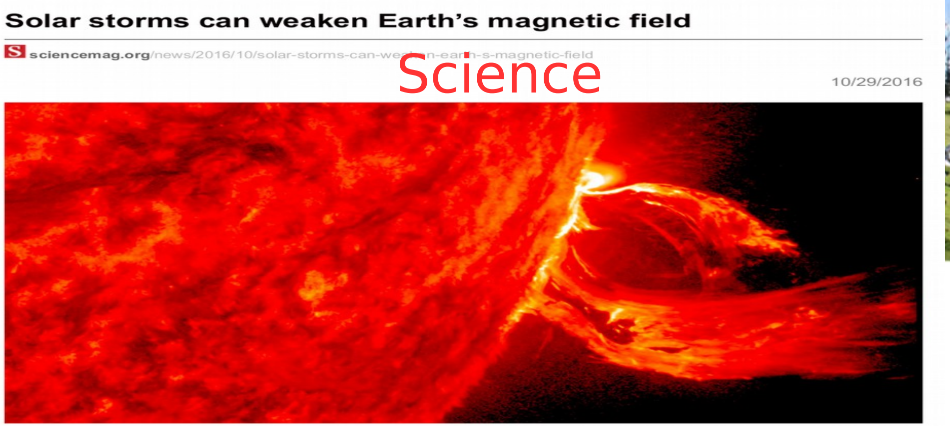
(Received 16 June 2016; published 20 October 2016)

The GRAPES-3 tracking muon telescope in Ooty, India measures muon intensity at high cutoff rigidities (15–24 GV) along nine independent directions covering 2.3 sr. The arrival of a coronal mass ejection on 22 June 2015 18:40 UT had triggered a severe G4-class geomagnetic storm (storm). Starting 19:00 UT, the GRAPES-3 muon telescope recorded a 2 h high-energy (~20 GeV) burst of galactic cosmic rays (GCRs) that was strongly correlated with a 40 nT surge in the interplanetary magnetic field (IMF). Simulations have shown that a large (17×) compression of the IMF to 680 nT, followed by reconnection with the geomagnetic field (GMF) leading to lower cutoff rigidities could generate this burst. Here, 680 nT represents a short-term change in GMF around Earth, averaged over 7 times its volume. The GCRs, due to lowering of cutoff rigidities, were deflected from Earth's day side by ~210° in longitude, offering a natural explanation of its night-time detection by the GRAPES-3. The simultaneous occurrence of the burst in all nine directions suggests its origin close to Earth. It also indicates a transient weakening of Earth's magnetic shield, and may hold clues for a better understanding of future superstorms that could cripple modern technological infrastructure on Earth, and endanger the lives of the astronauts in space.

DOI: 10.1103/PhysRevLett.117.171101

World coverage: 1096 reports in 119 countries in 37 languages



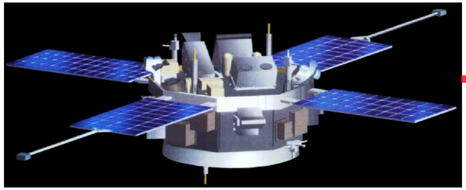


A coronal mass ejection in 2015, seen here by NASA's Solar Dynamics Observatory, ended up weakening Earth's magnetic field.

Solar Dynamics Observatory, NASA

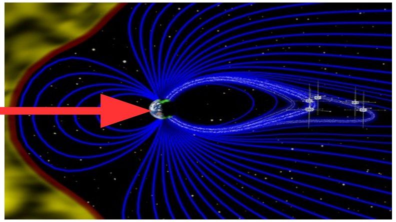
22 June2015 event: Time delay (28 min)

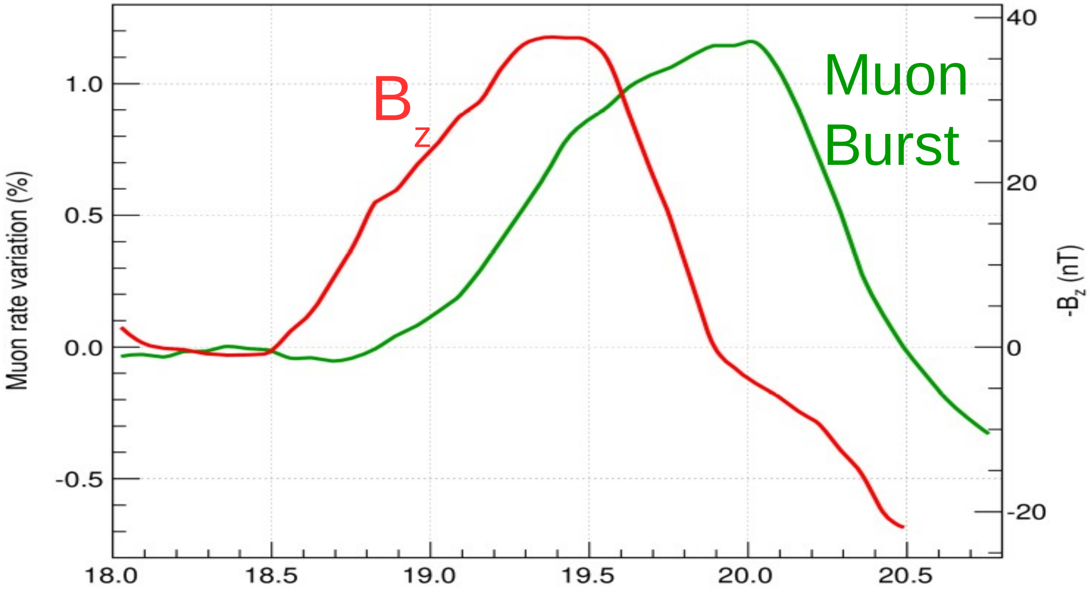
L1 point

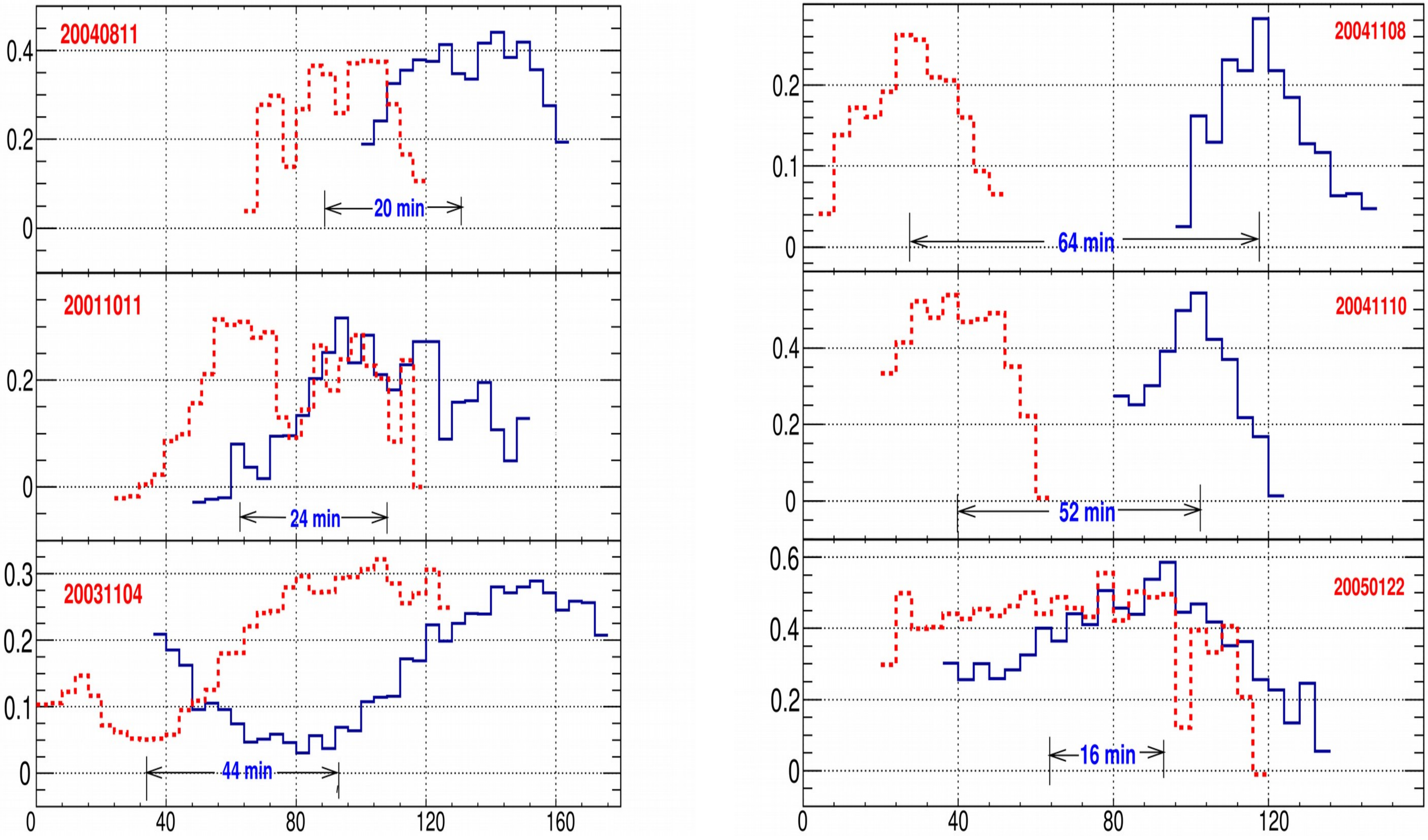


1.5 million km (36 min)

Plasma velocity = 700 km/s







20040811
20 min
20011011
24 min
20031104
44 min
20041108
64 min
20041110
52 min
20050122
16 min

Perspective

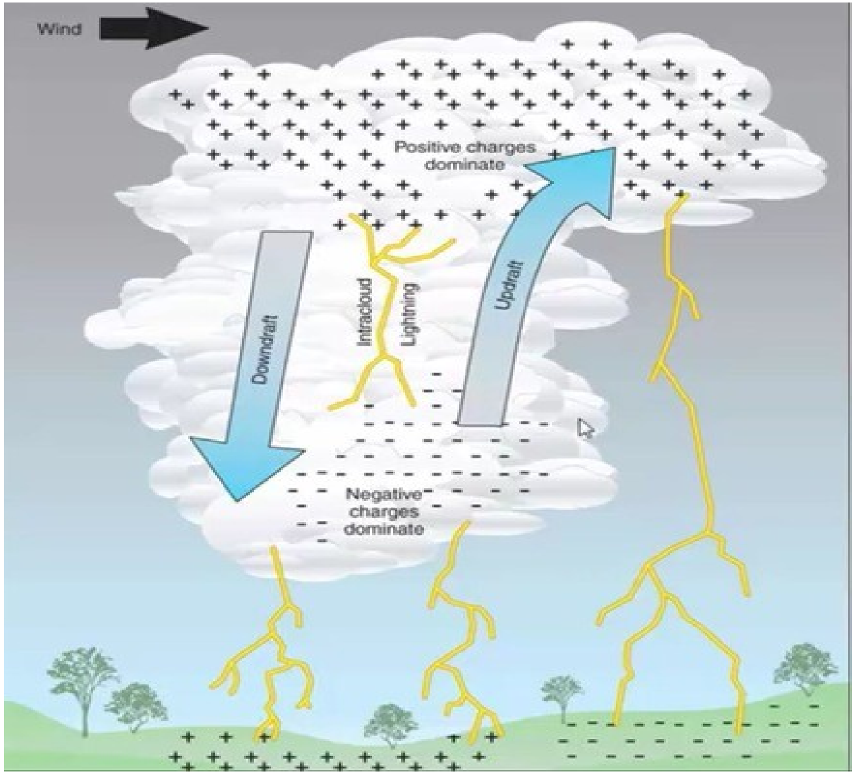
(1) NAS, USA reports that a super storm (July 2012 missed Earth) can disrupt satellites in space, communication systems and electronic devices on ground, short-circuit transformers, may cause losses of trillions of dollars.

(2) Early warning spacecrafts may get disabled. However, GRAPES-3 due to equatorial location on Earth is well-shielded, will continue to operate providing valuable data.

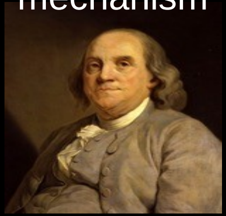
(3) GRAPES-3 discovery shows that cosmic rays can be used as as effective tool for probing space weather

(4) Large analysis effort to better understand existing 19 years of data for signs of storm-like events. Algorithms to predict storms using known events (may be using Artificial Neural Network).

Thundercloud potential



B. Franklin
Charging
mechanism



1750s

1920s

C.T.R. Wilson’s
prediction of
1 GV 90Y ago

Discovery of Terrestrial gamma ray
flashes (TGFs) by CGRO

1994

2001

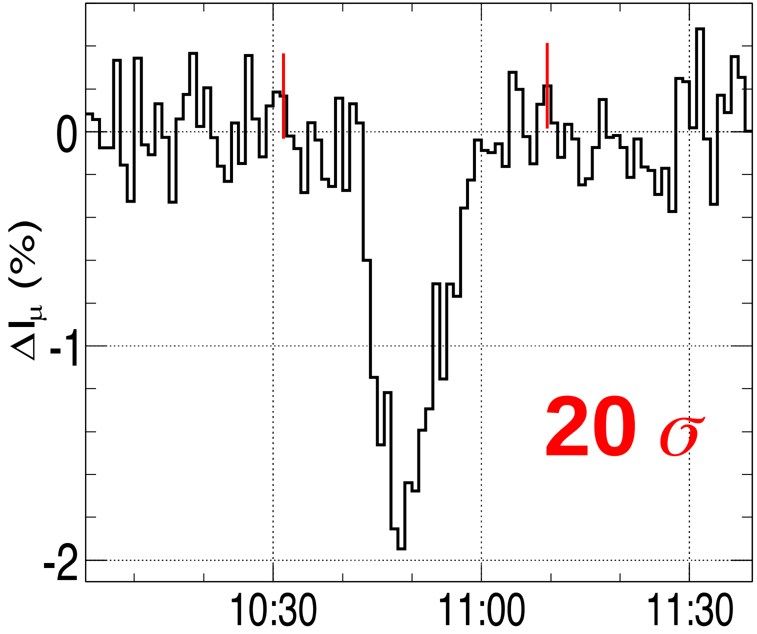
Measurement of
0.13 GV

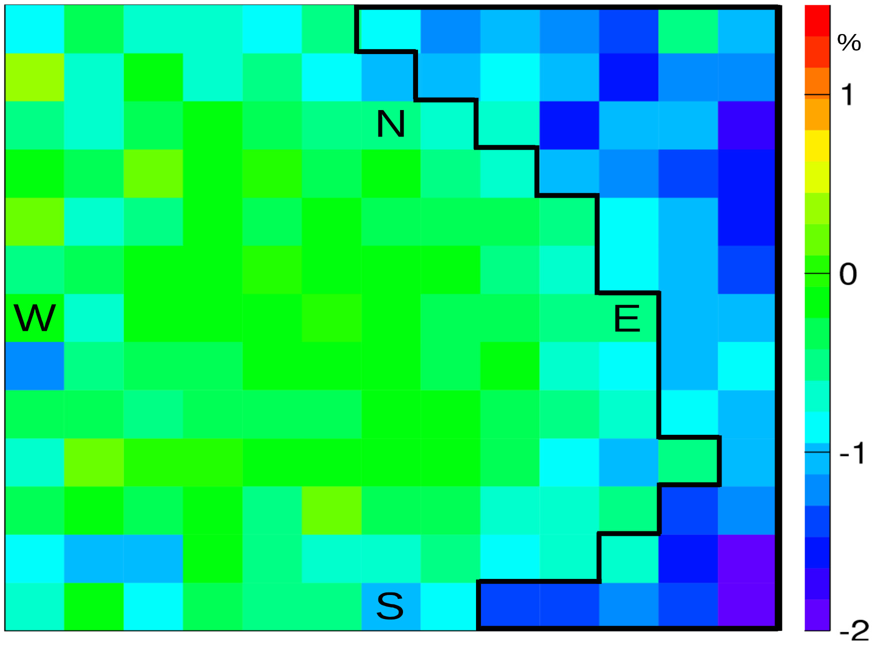
Detection of 100 MeV gamma rays
in TGFs by AGILE

2011

GRAPES-3 has recorded 184 thunderstorm events during April 2011- December 2014

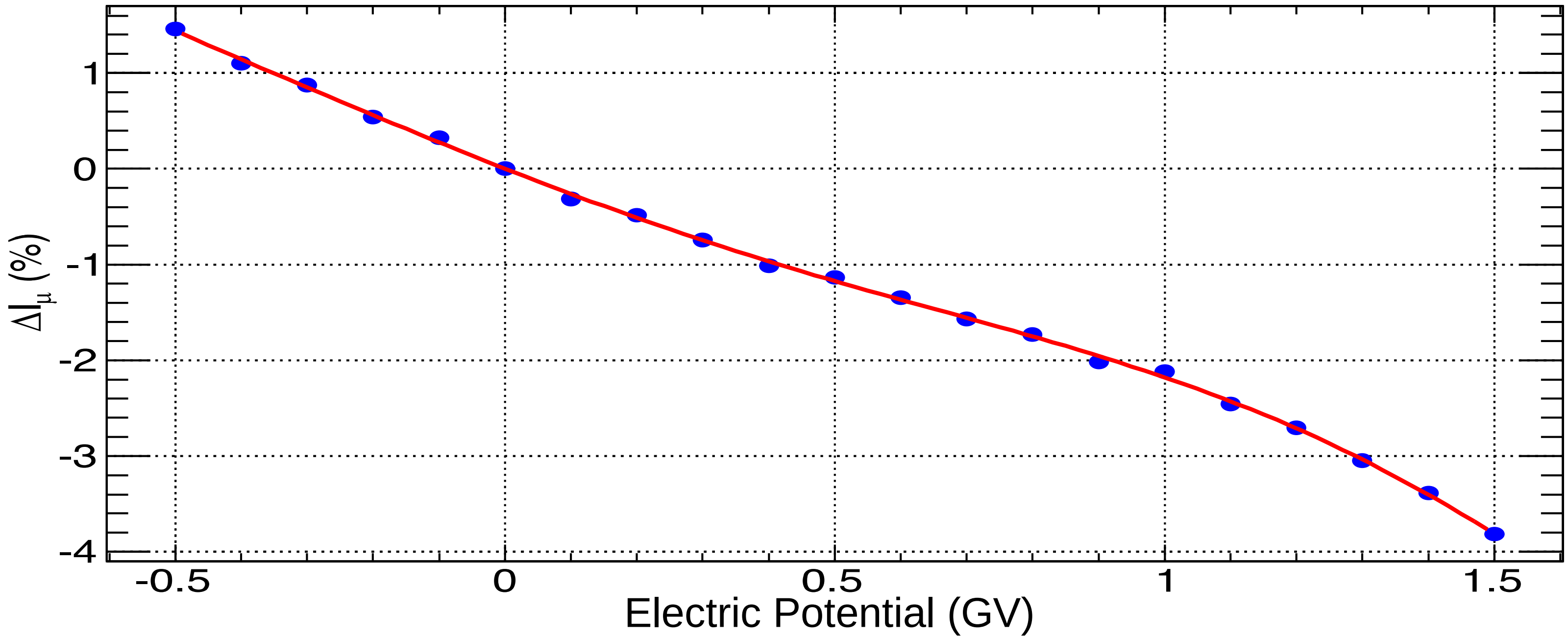
1 December 2014 Event





As $\mu^+/\mu^- > 1$, deceleration of μ^+ and acceleration of μ^- would result a net decrease. Since GRAPES-3 records muons >1 GeV, so it requires GeV potential to make any change in the muon intensity

Voltage profile with Monte-Carlo Simulation



1.3 GV was estimated for 1 December 2014 Event

PHYSICAL REVIEW LETTERS **122,** 105101 (2019)

Editors' Suggestion Featured in Physics

Measurement of the Electrical Properties of a Thundercloud Through Muon Imaging by the GRAPES-3 Experiment

B. Hariharan,[1,2] A. Chandra,[1,2] S. R. Dugad,[1,2] S. K. Gupta,[1,2,*] P. Jagadeesan,[1,2] A. Jain,[1,2] P. K. Mohanty,[1,2] S. D. Morris,[1,2] P. K. Nayak,[1,2] P. S. Rakshe,[1,2] K. Ramesh,[1,2] B. S. Rao,[1,2] L. V. Reddy,[1,2] M. Zuberi,[1,2] Y. Hayashi,[2,3] S. Kawakami,[2,3] S. Ahmad,[2,4] H. Kojima,[2,5] A. Oshima,[2,5] S. Shibata,[2,5] Y. Muraki,[2,6] and K. Tanaka[2,7]

(GRAPES-3 Collaboration)

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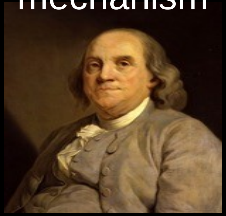
(Received 6 January 2019; revised manuscript received 21 January 2019; published 15 March 2019)

The GRAPES-3 muon telescope located in Ooty, India records rapid (~10 min) variations in the muon intensity during major thunderstorms. Out of a total of 184 thunderstorms recorded during the interval of April 2011–December 2014, the one on December 1, 2014 produced a massive potential of 1.3 GV. The electric field measured by four well-separated (up to 6 km) monitors on the ground was used to help estimate some of the properties of this thundercloud, including its altitude and area that were found to be 11.4 km above mean sea level and ≥ 380 km^2, respectively. A charging time of 6 min to reach 1.3 GV implied the delivery of a power of ≥ 2 GW by this thundercloud that was moving at a speed of ~60 km h^{-1}. This work possibly provides the first direct evidence for the generation of gigavolt potentials in thunderclouds that could also possibly explain the production of highest-energy (100 MeV) gamma rays in the terrestrial gamma-ray flashes.

DOI: 10.1103/PhysRevLett.122.105101

B. Franklin
Charging
mechanism



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2001

Measurement of
0.13 GV

Detection of
100 MeV γ-ray in
TGFs

2011

2019

Measurement of
1.3 GV

nature

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PHYSICS · 22 MARCH 2019

Supercharged thunderstorm reaches a record 1.3 billion volts

Forbes

Cosmic Ray Hunters Spy Record-Breaking 1.3-Billion-Volt Thunderstorm

Science

Massive voltages in thunderclouds can slow down subatomic particles

NATIONAL GEOGRAPHIC

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Most powerful electrical storm on record detected

The total charge in a single thundercloud could have powered New York City for half an hour.

CNN Home

The astonishing power of a thunderstorm

TH Ooty's muon detection facility m

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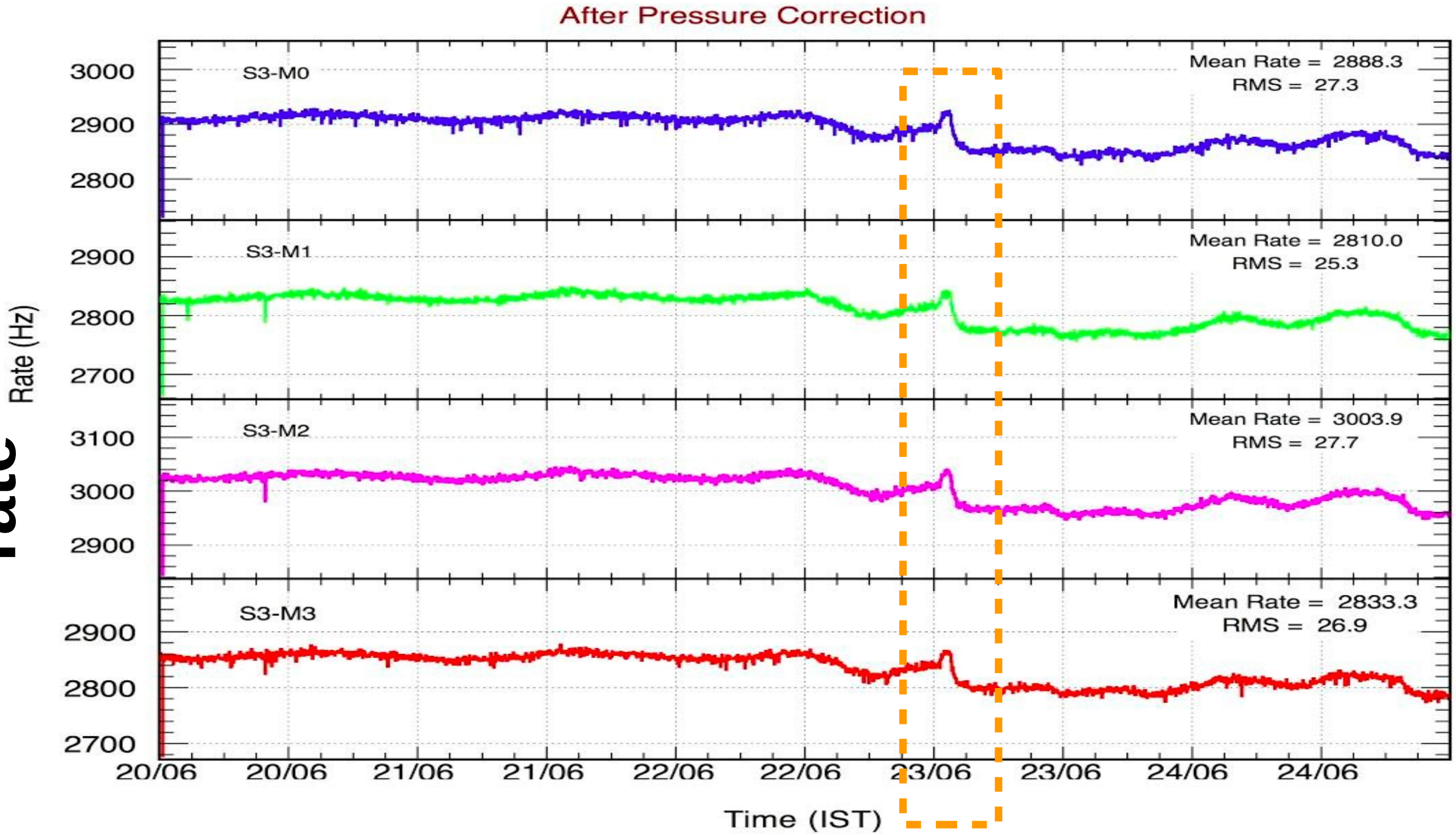
SCIENCE

Ooty's muon detection facility measures potential of thundercloud


130
172
129
093
063
171

Muon burst on 22 June 2015 Ooty midnight

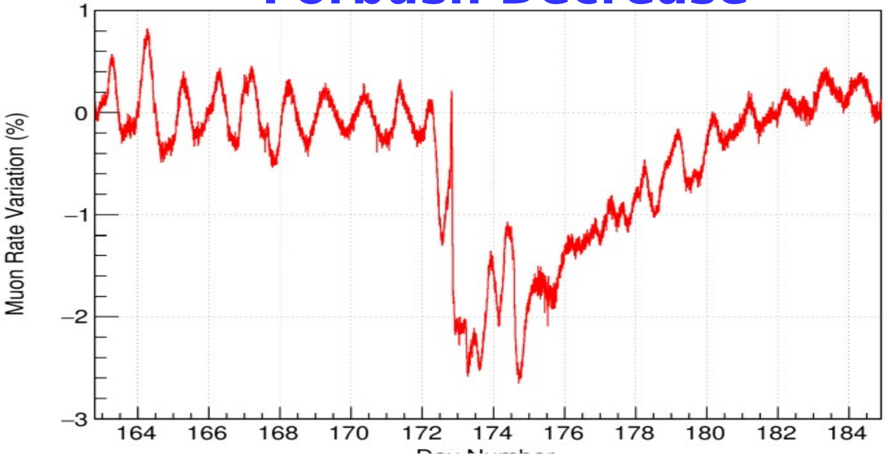
Muon rate

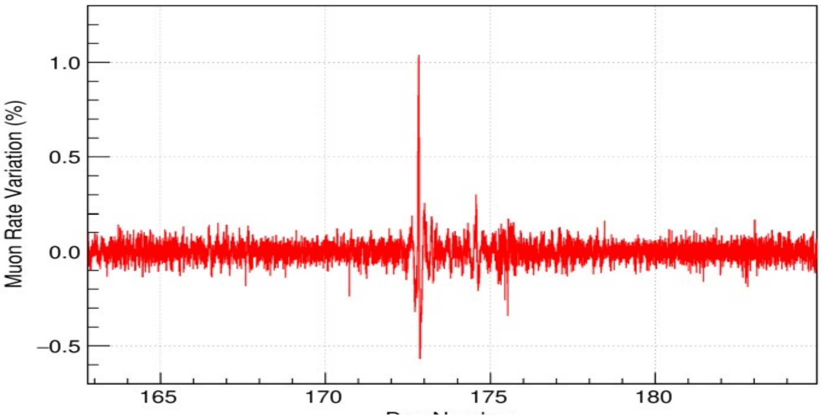


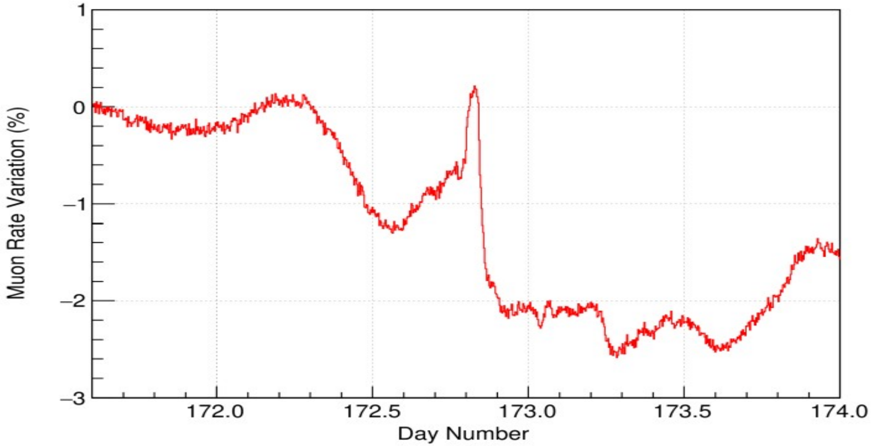
Rate went up by 1% in all 16 modules for 2 hours

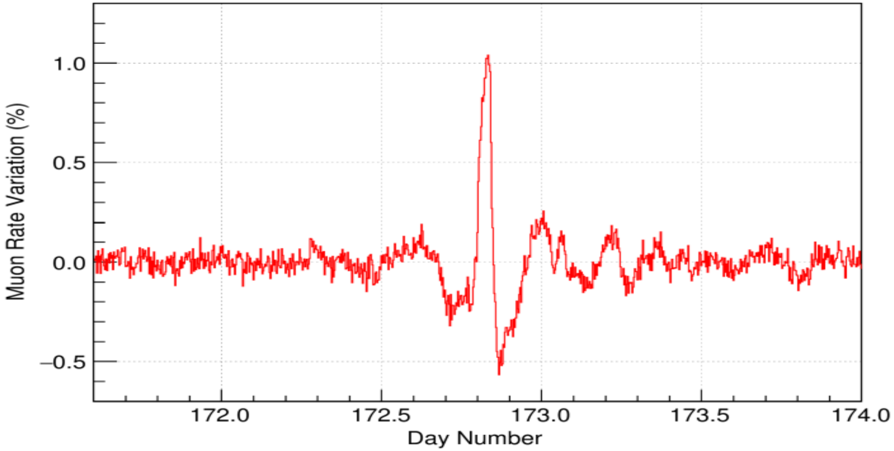
Fast Fourier Transform Analysis

Forbush Decrease







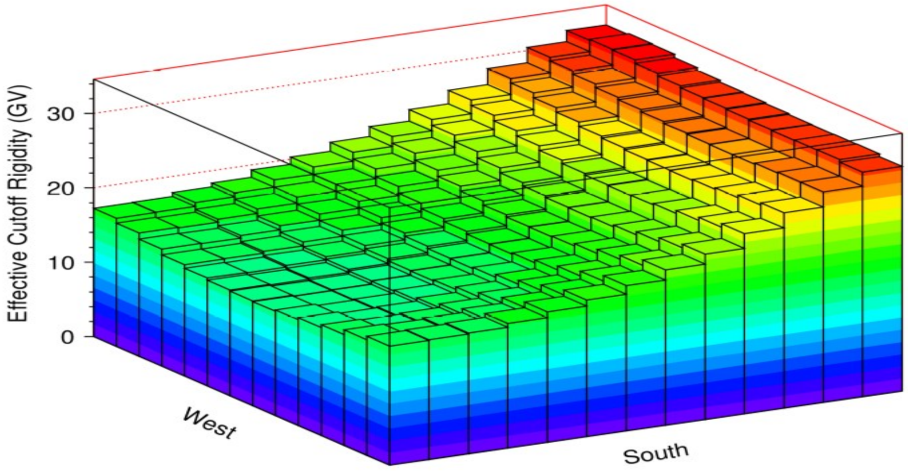


Connection between Muon Burst and IMF

Hypothesis

Transient weakening of geomagnetic field due to magnetic reconnection for two hours leading to lowering of cutoff rigidity and allowing low energy cosmic rays to enter earth's atmosphere

Cutoff rigidity map for GRAPES-3



14 GV in West to 32 GV in East

Simple Model

Vector addition of geomagnetic field and time dependent IMF

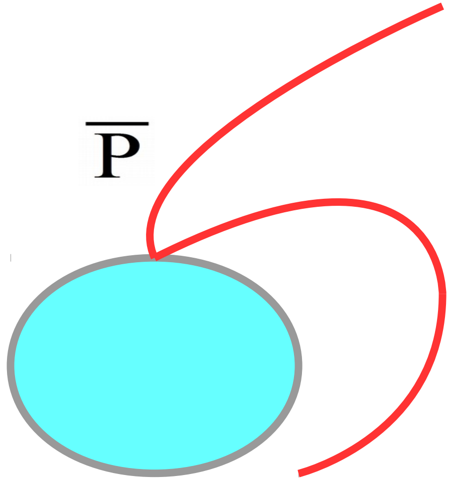
Computation of cutoff rigidity

An antiproton is launched from Earth's surface to 25Re in geomagnetic field modeled by International Geomagentic

$$\frac{\mathrm{d}v_r}{\mathrm{d}t} = \frac{e}{mc}(v_\theta B_\phi - v_\phi B_\theta) + \frac{v_\theta^2}{r} + \frac{v_\phi^2}{r},$$

$$\frac{\mathrm{d}v_\theta}{\mathrm{d}t} = \frac{e}{mc}(v_\phi B_r - v_r B_\phi) - \frac{v_r v_\theta}{r} + \frac{v_\phi^2}{r \tan\theta},$$

$$\frac{\mathrm{d}v_\phi}{dt} = \frac{e}{mc}(v_r B_\theta - v_\theta B_r) - \frac{v_r v_\phi}{r} - \frac{v_\theta v_\phi}{r \tan\theta}.$$



Back tracing

If antiproton returns to Earth instead of escaping into space which means a proton of same rigidity from space can not reach Earth and this value of rigidity is called cutoff rigidity (Rc)

A cutoff rigidity map was generated in 360 (azimuth angle) x 70 (zenith angle values) directions. Each direction a large number of trajectories to be computed starting with a rigidity well above the expected cutoff rigidity in steps of 0.01 GV

Simulation of cosmic ray interaction in the atmosphere

10^9 protons

θ=0–70°, Φ=0-360°

Cutoff rigidity check

Atmospheric simulation using CORSIKA

Detector simulation

Muon counts in 169 directions