Synergy of ICAL with GRAPES-3

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On behalf of the GRAPES-3 collaboration

International Workshop on Outlook for INO, IICHEP and beyond, 19-20 February 2021

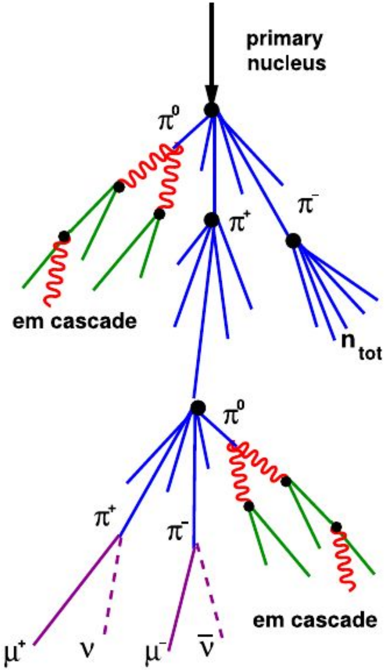
Outline

- Introduction to GRAPES-3 experiment
- GRAPES-3 detector R&D
- Physics objectives
- Complementary physics capabilities of GRAPES-3 and ICAL
  - Thunderstorm physics
  - Solar physics

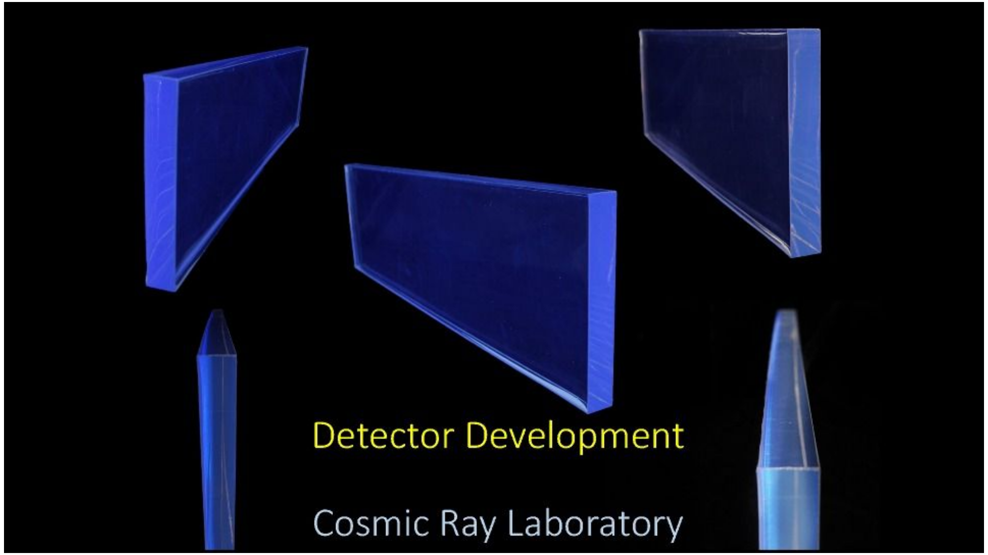
The GRAPES-3 experiment at Ooty (2200 m)

400 plastic scintillator detectors (1 m^2 area) with 8 m inter-separation spread over 25,000m^2

560 m^2 muon telescope consisting 3712 proportional counters (6m x 0.1m x 0.1m)



In-house development of plastic scintillators



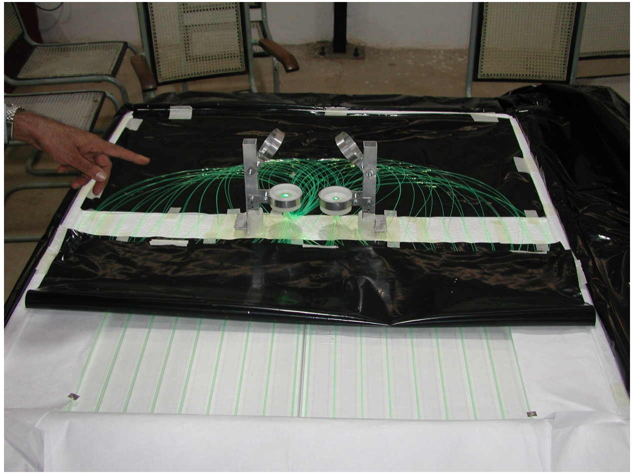
Plastic Scintillator development:

Decay Time= 1.6 ns Light Output = 85% Bicron (54% anthracene)

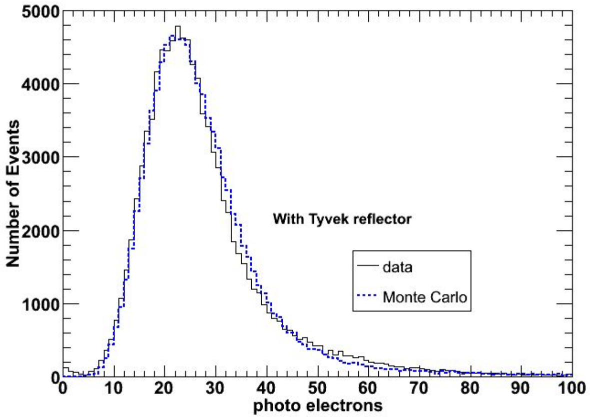
Timing 25% faster Atten. Length λ= 100cm Cost ~30% of Bicron

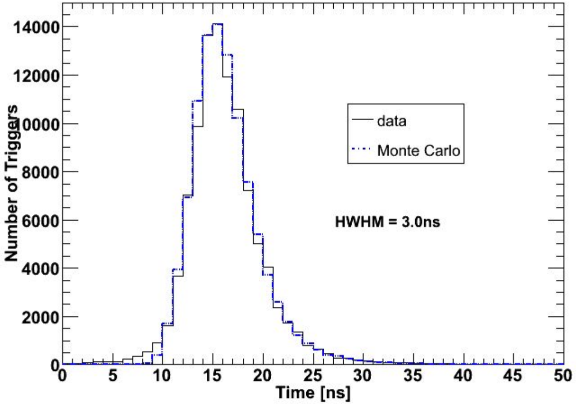
Max Size 100cmX100cm Total > 2000

CERN, Osaka, IUAC Delhi, Bose, VECC, BARC, ECIL, Utkal U. Dayalbag Inst., IISER Pune

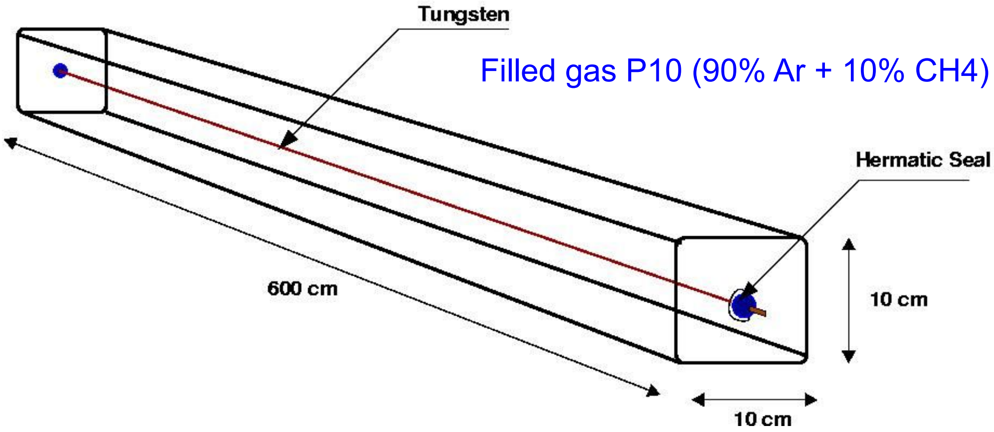



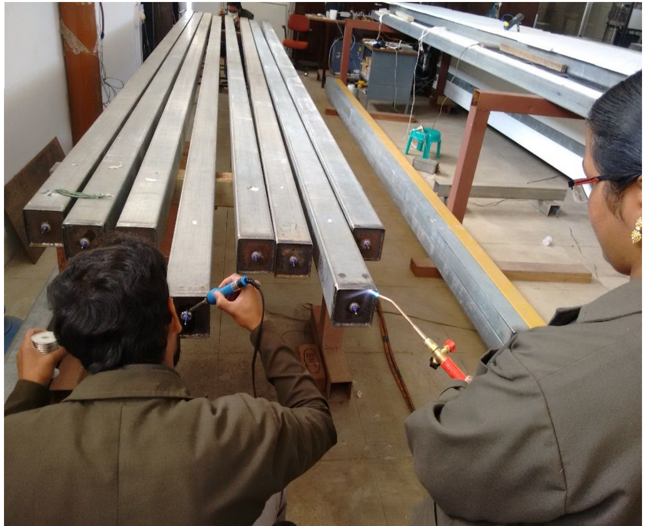
Monte Carlo code **G3sim** for simulation of plastic scintillator detectors with wavelength shifter fiber readout, P.K. Mohanty et al., Rev. Sci. Istr. 83 043301 (2012)



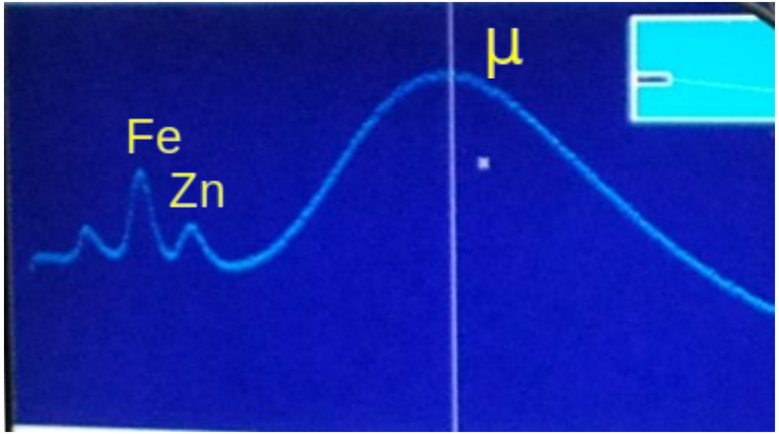


Proportional counters from iron tubes





Evacuation, filling and testing



Construction of new muon telescope


14 October 2019

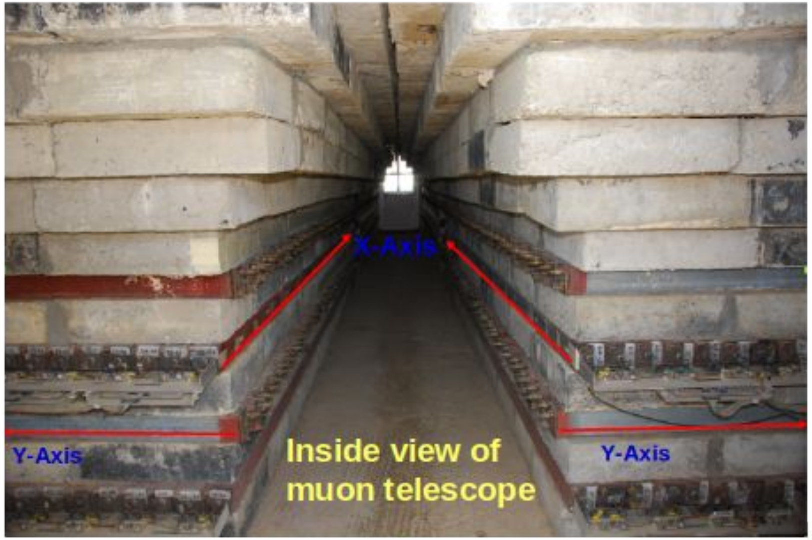

Inside view of muon telescope

Scientific objectives of GRAPES-3

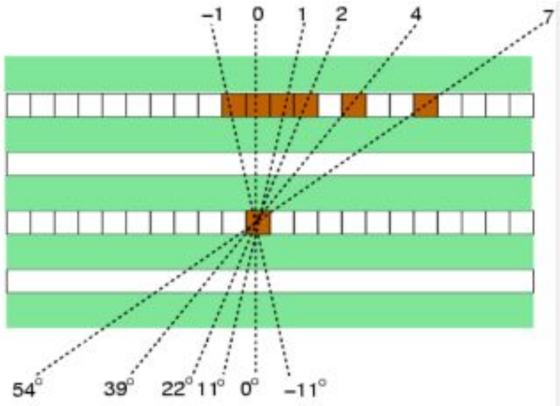
(Understanding high energy particle acceleration in various astrophysical settings)

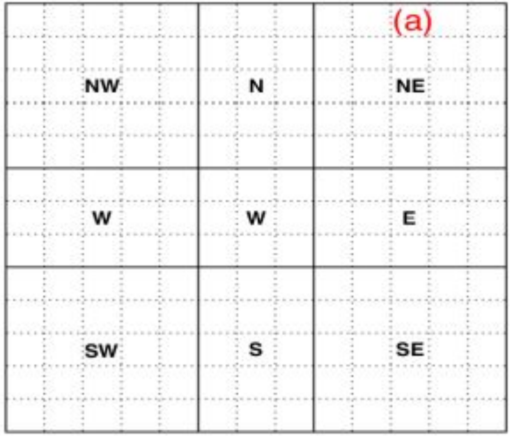
1. Particle acceleration by electric potential in thunderstorms.
2. Space weather and heliospheric physics
3. Cosmic ray energy spectrum and composition over 10^{12}-10^{17} eV.
4. Investigation of composition dependence of CR anisotropy in TeV-PeV range
5. Search for point-like gamma ray sources above 50 TeV to identify the accelerators of Galactic cosmic rays at PeV energies
6. Search for multi-TeV diffuse gamma ray flux from Galactic disk
7. Indirect searches for 'dark matter' in the PeV mass range

GRAPES-3 Muon Telescope (Ooty, India, 11.4°N, 76.7°E)

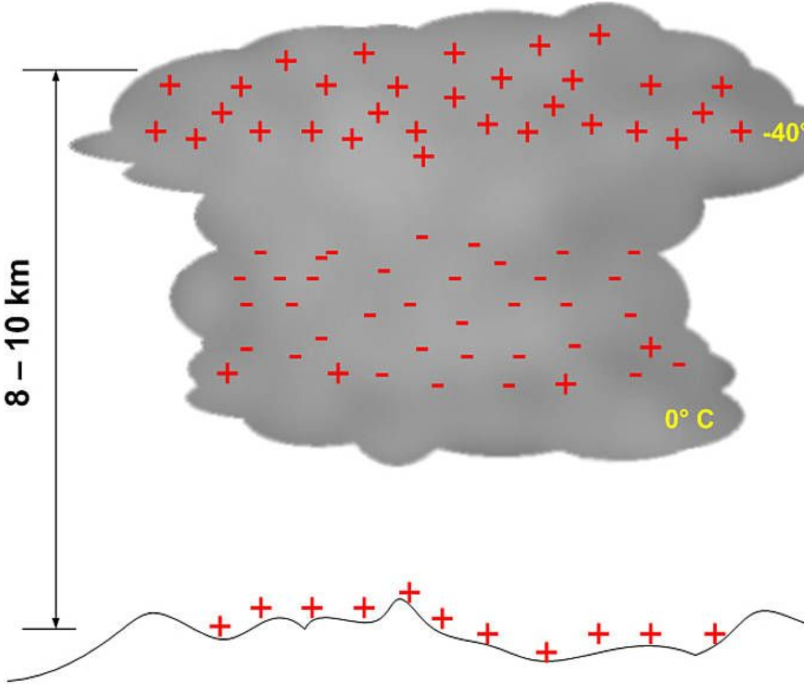


Modules	**16 (35 m^2 each)**
Total Area	**560 m^2**
Directions	**13 x 13 = 169**
Field of view	**2.3 sr**
Avg angular res.	**4°**
Muon rate	**5×10^4 s^{-1}**
Sensitivity	0.1% / minute
Cutoff rigidity	14-32 GV
Median rigidity	65-140 GV



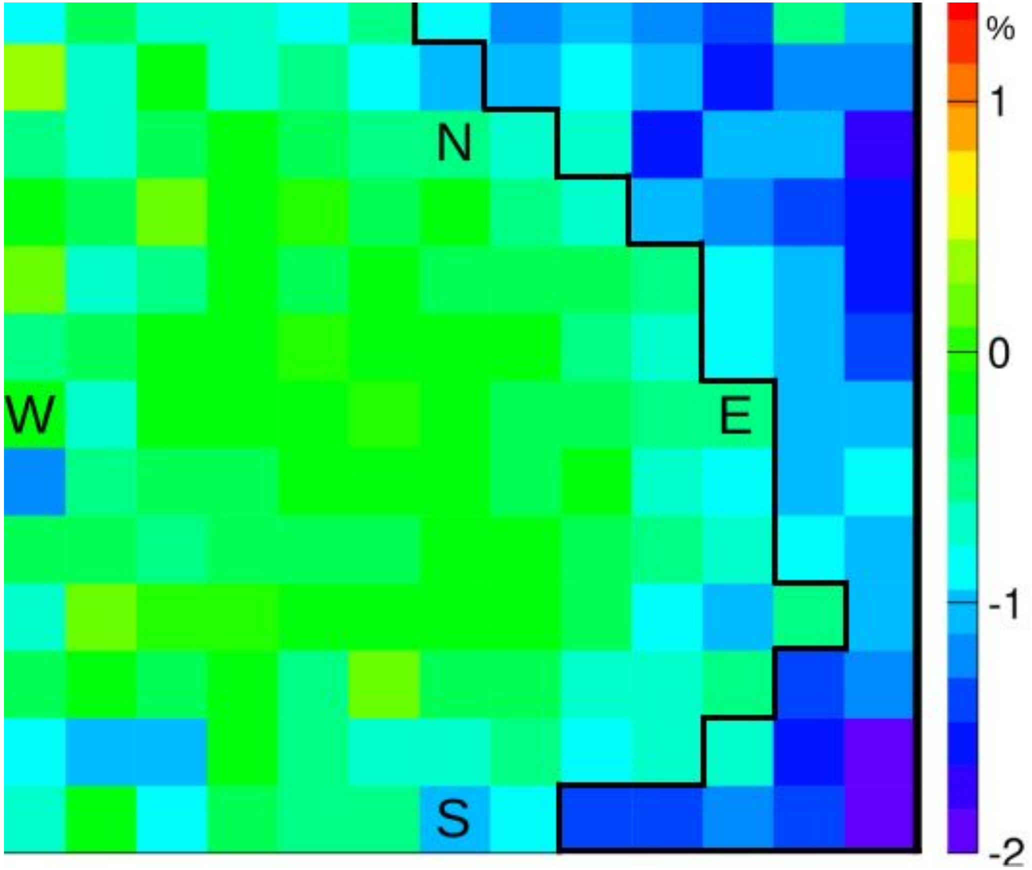


Thunderstorms



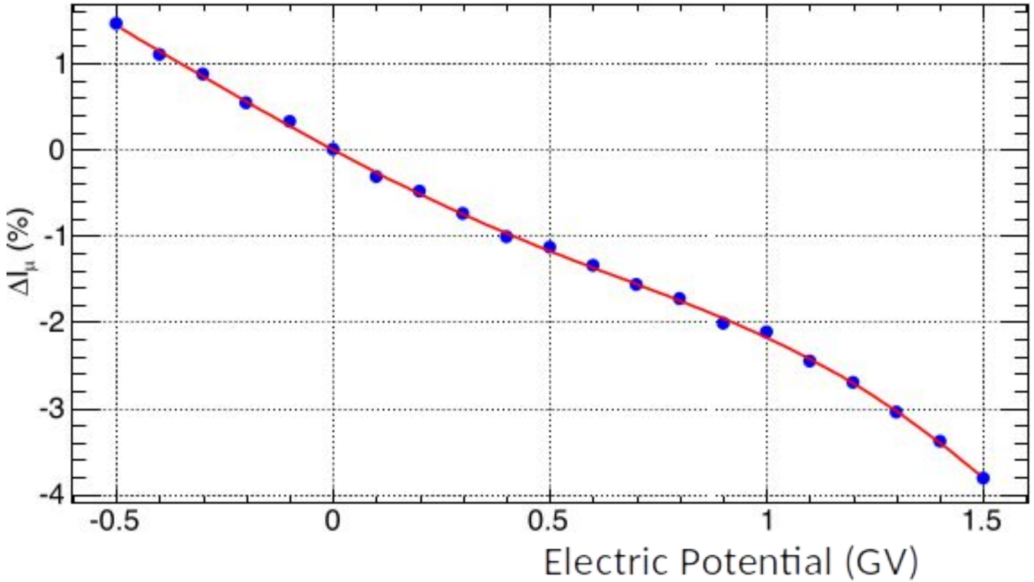
- Dipolar structure (actual structure is complex)
- V >1 billion volts (predicted by C.T.R. Wilson 90 years ago)

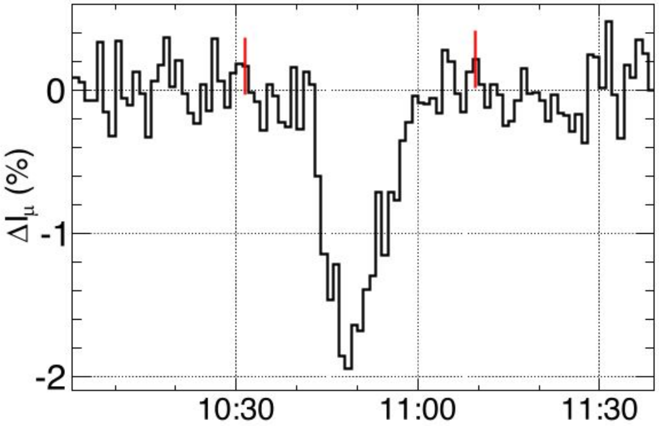
Muon image of 1st Dec 2014 event

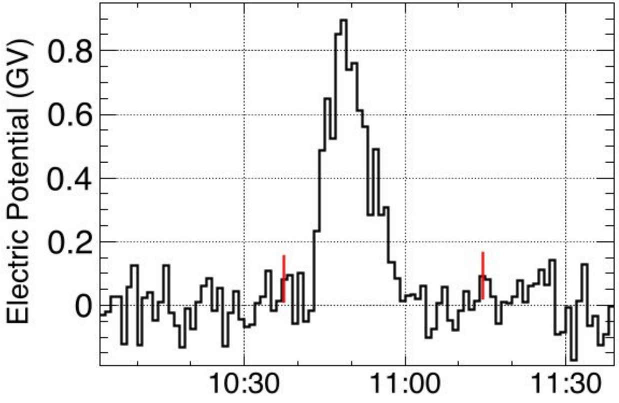


Since μ+/μ- > 1 deceleration of μ+ and acceleration of μ- would result a net decrease and vice versa

Monte Carlo simulation

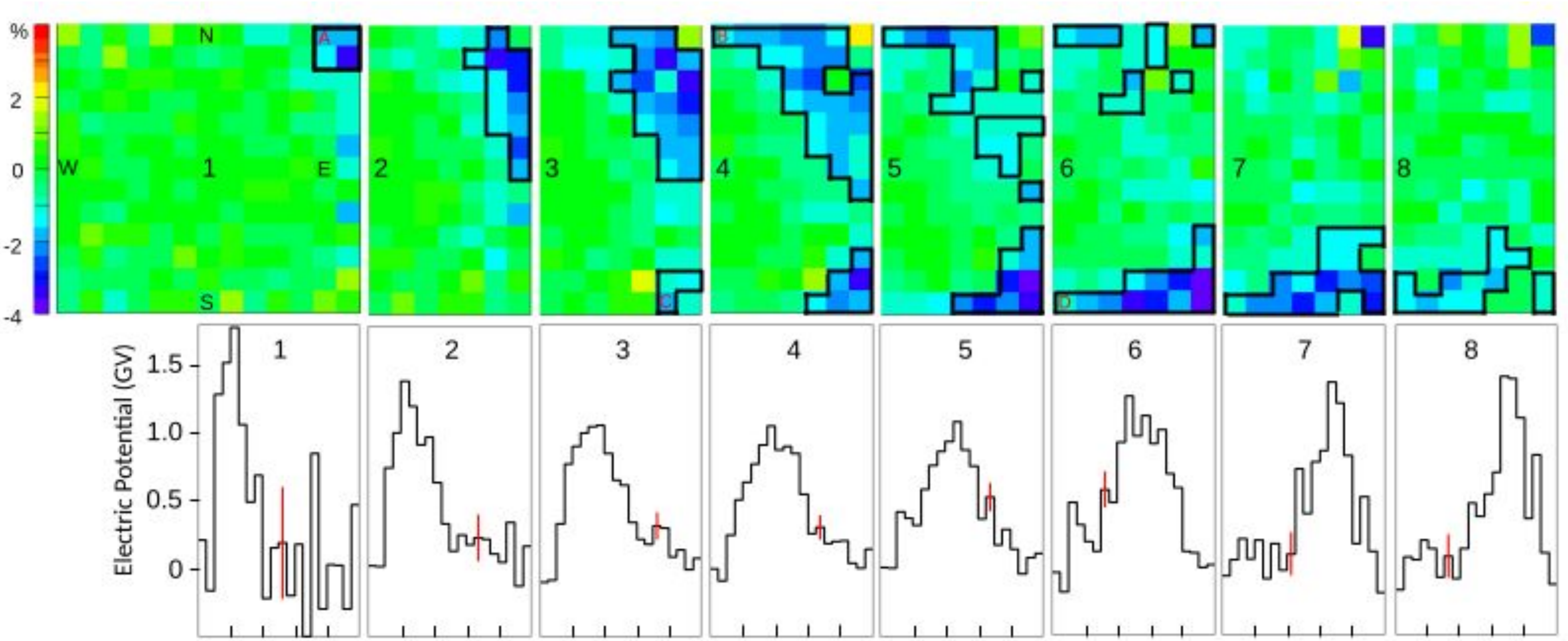






- $\Delta I_{\mu(Peak)} = (-2 \pm 0.2)$ %
- $V_{Peak} = (0.90 \pm 0.08)$ GV

Cloud movement



- Mean V = 1.3 GV
- Angular Velocity = 6.2° min^{-1}

Electrical properties of the cloud

- Mean V = 1.3 GV
- Lin. Vel. = 60 km hr^{-1}
- Ang. Vel. = 6.2° min^{-1}
- Height = 11.4 km amsl
- Radius ≥ 11 km
- Area ≥ 380 km^2
- C ≥ 0.85 μF
- Q ≥ 1100 C
- E ≥ 720 GJ
- P ≥ 2 GW

- Comparable to biggest nuclear reactors/hydroelectric/thermal power plants
- Enough to power a big city like Mumbai for the duration of the thunderstorm

Giga-Volt natural particle accelerator above our head !!!

Benjamin 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 γ-ray in TGFs

2011

2019

Measurement of 1.3 GV

[redacted]

Measurement of electrical properties of a thundercloud through muon imaging by the GRAPES-3 experiment, Physical Review Letters 122 (2019) 105101

nature | Subscribe

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 | Subscribe

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 ... SHARE ON

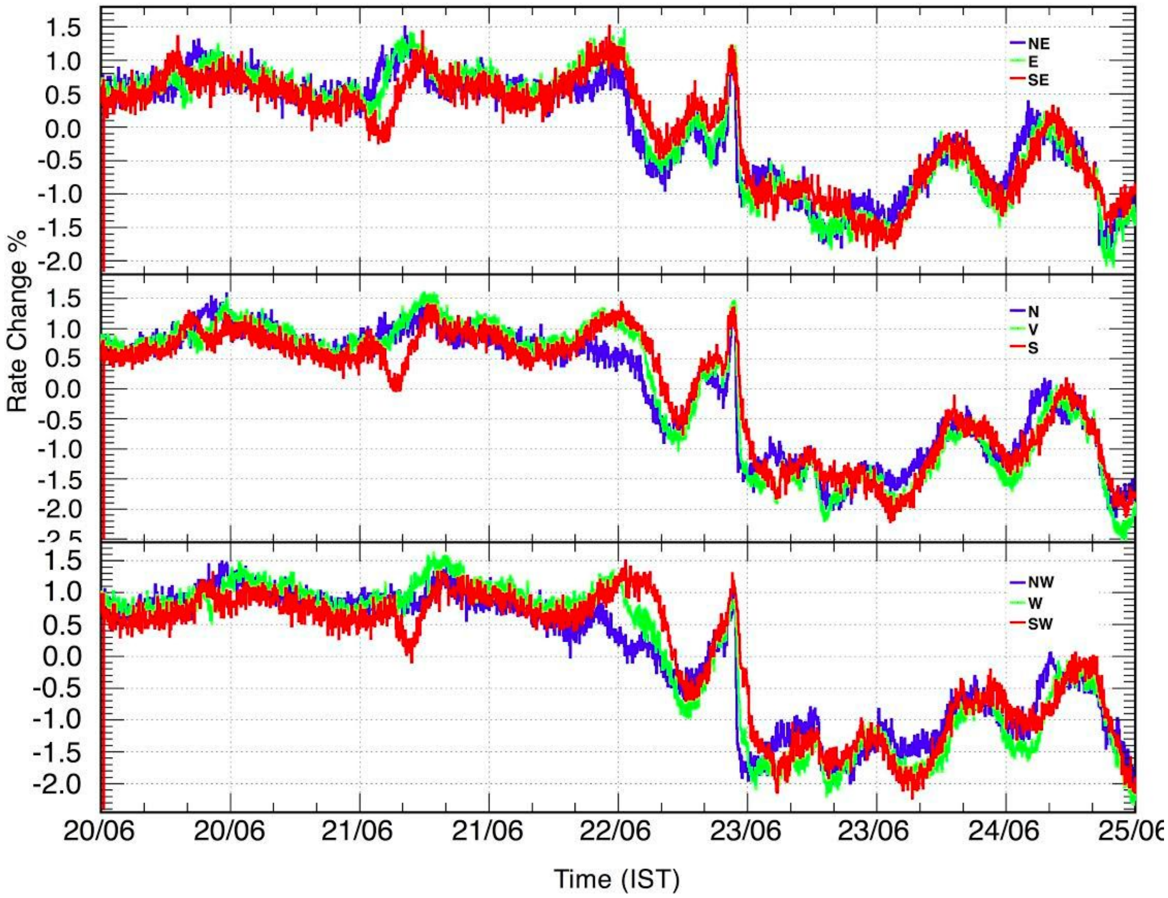
SCIENCE

Ooty's muon detection facility measures potential of thundercloud

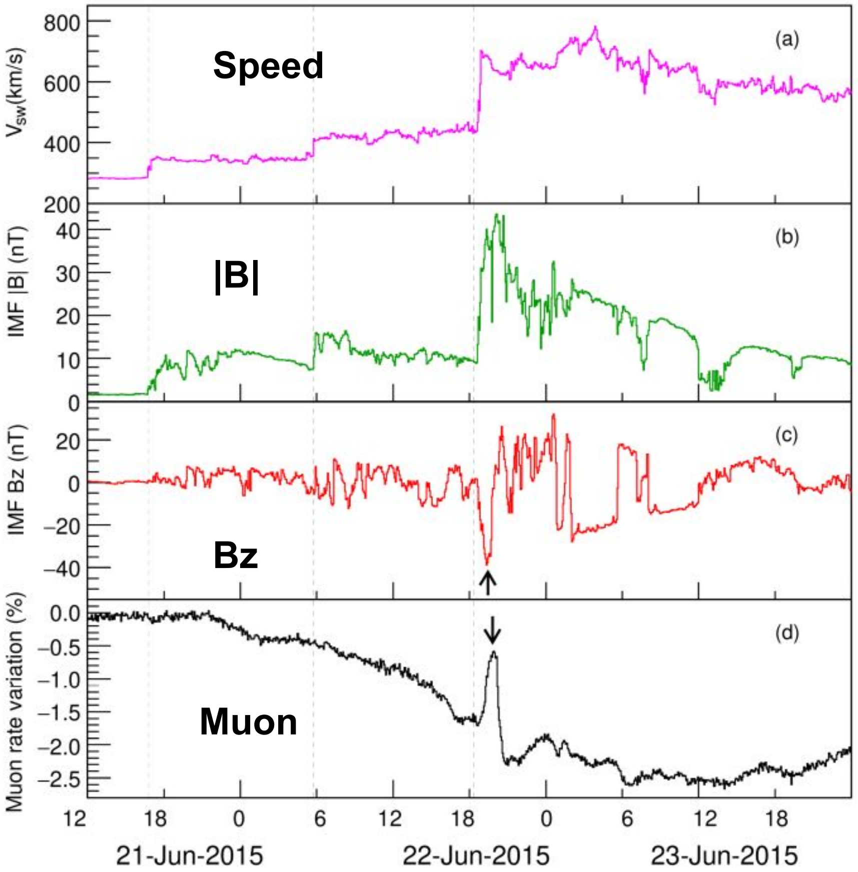
Thunderstorm physics with ICAL

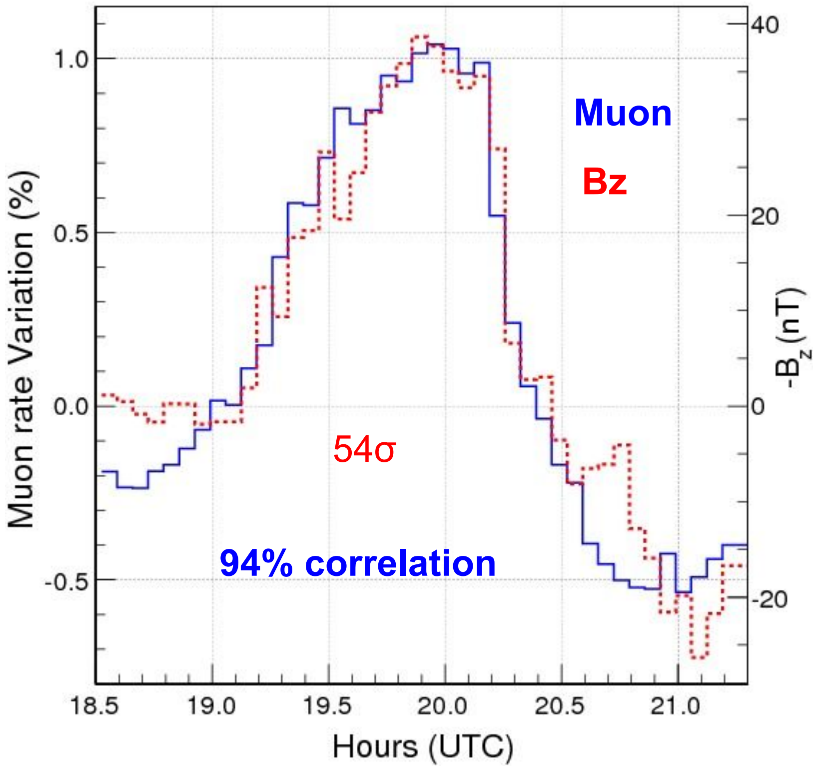
- The engineering ICAL detector (8m x 8m) will detect ~6000 muons per second of energy > GeV with a statistical precision of ~0.2% on a minute time scale.
- Therefore, a change of 1% of muon flux during a thunderstorm event can be measured with 5 sigma effect.
- The ICAL's ability to measure μ+ and μ- separately could help to establish the phenomenon of charged particle acceleration by thunderstorm electric field directly.

Muon burst at Ooty midnight of 22 June 2015

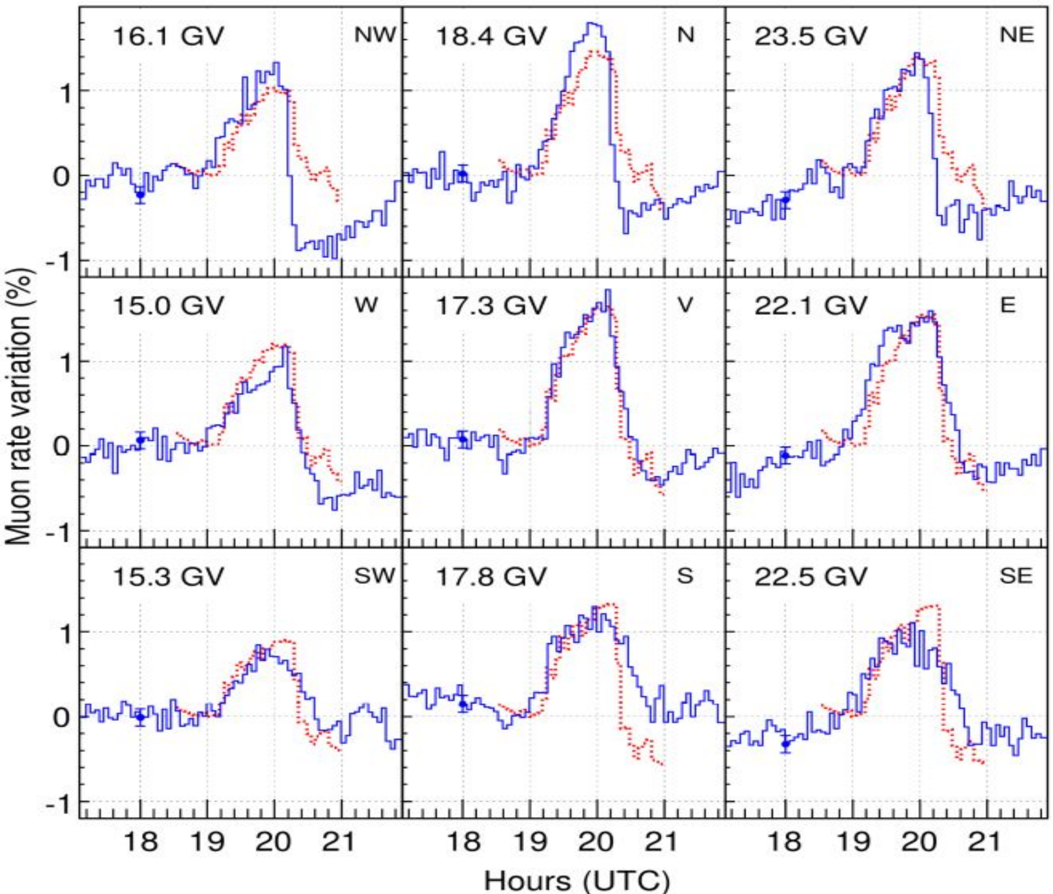


A coronal mass ejection on 22 June 2015





Simulation of the muon burst



Result: Earth’s magnetic field weakened by 680 nT

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

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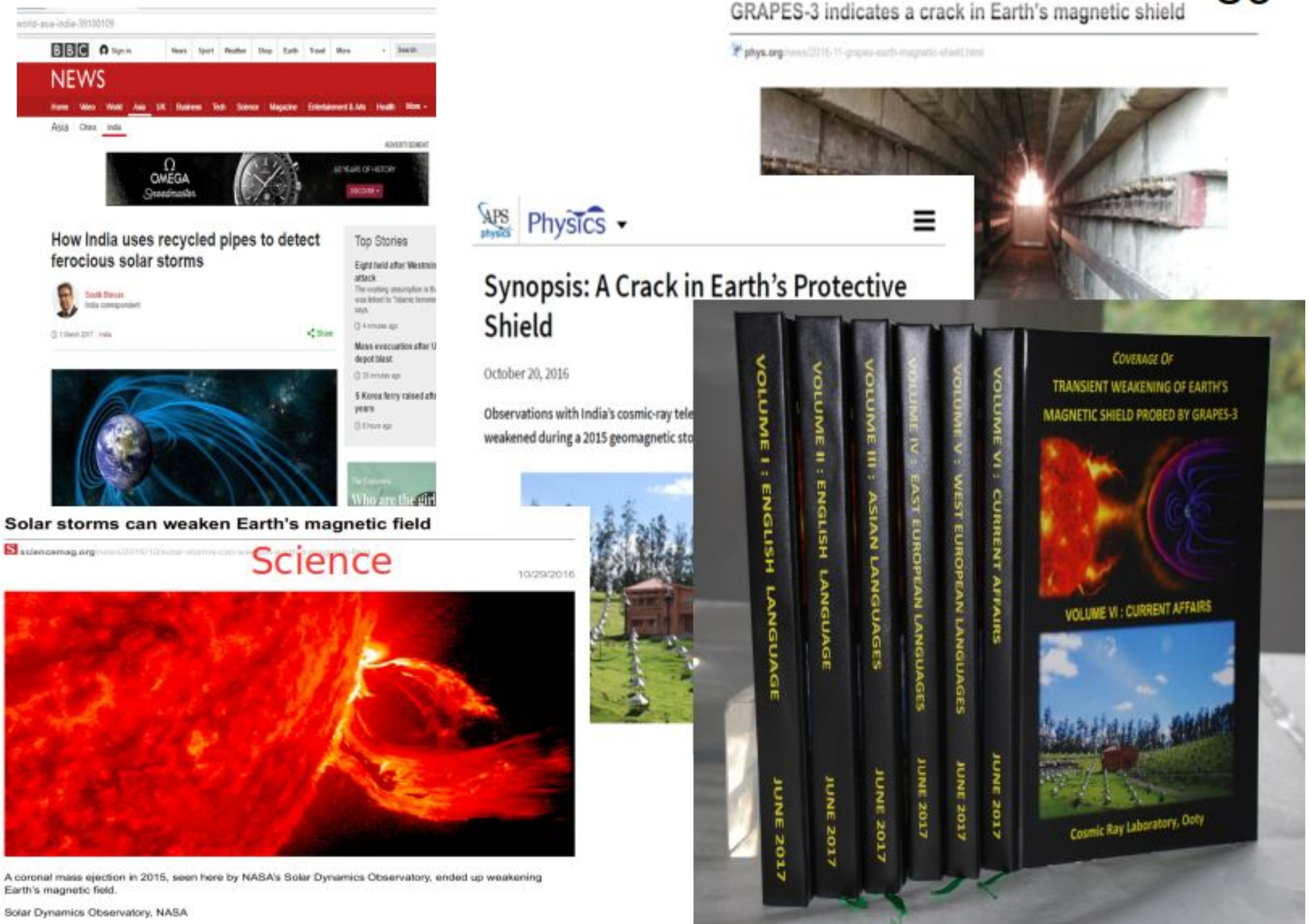
(Received 16 June 2016; published 20 October 2016)

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.

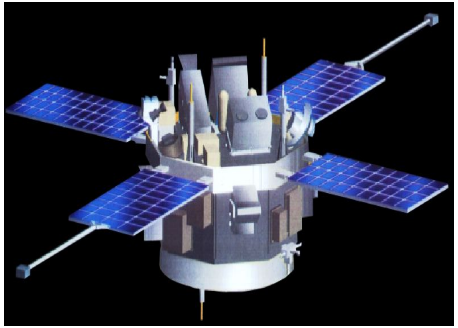
DOI: 10.1103/PhysRevLett.117.171101

World coverage: 1096 reports in 119 countries in 37 languages

36

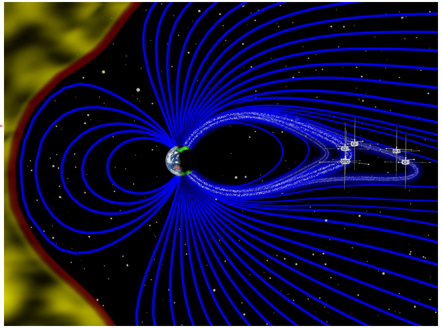


22 June 2015 event - Delay of storm arrival

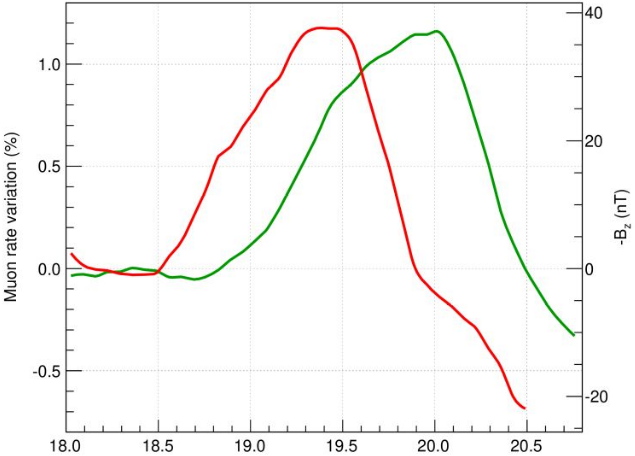


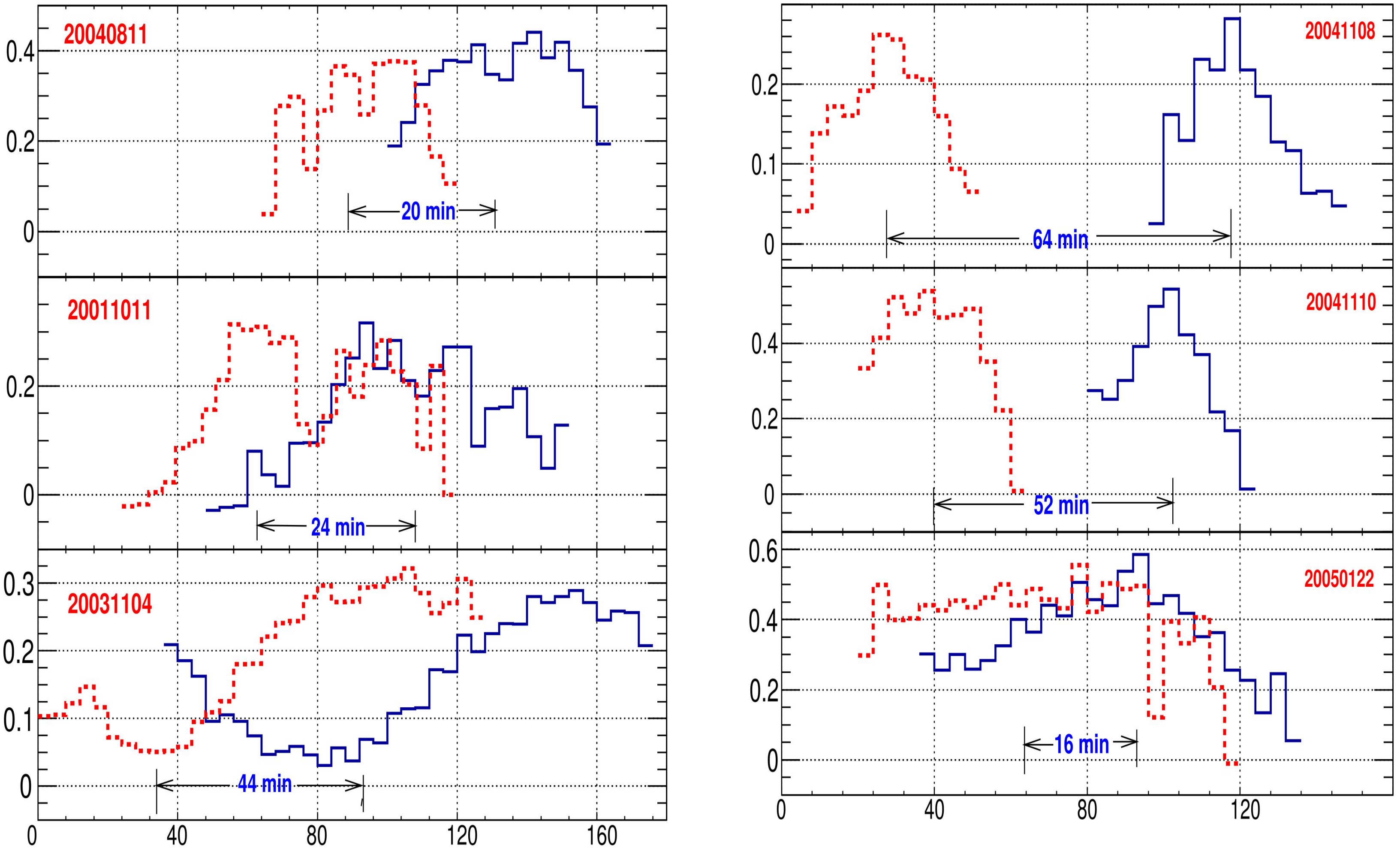
Plasma speed = 700 km/s

1.5 million km



36 minutes to cover 1.5 million km distance between L1 and Earth.
Burst event shows additional 28 minute delay (36+28=64 minutes)




20040811
20 min
20011011
24 min
20031104
44 min
20041108
64 min
20041110
52 min
20050122
16 min
0
0.1
0.2
0.3
0.4
0.6
40
80
120
160

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.

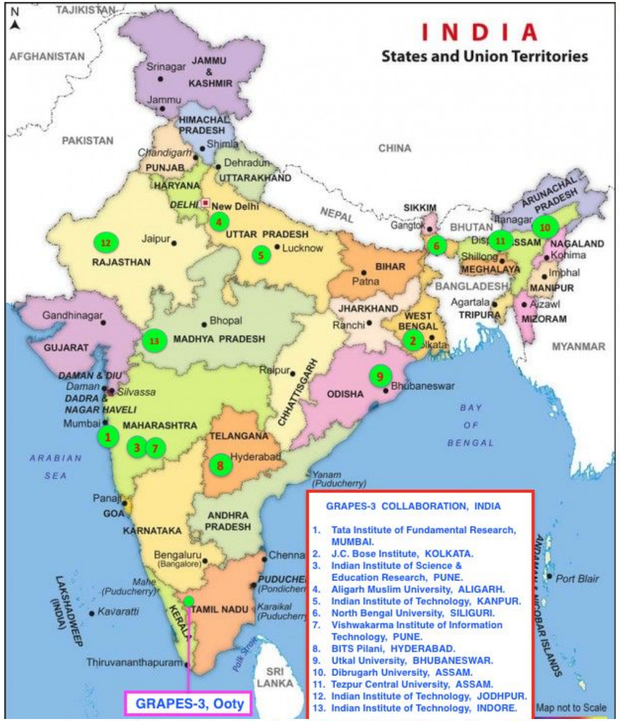
(3) GRAPES-3 discovery shows that cosmic rays can be used as as effective tool for probing space weather

(4) Large analysis effort to better understand existing 20 years of data for signs of storm-like events. Algorithms to predict storms using known events (may be using Artificial Neural Network).

Solar studies with GRAPES-3 and ICAL

- GRAPES-3 (11.4°N, 76.7°E), Engineering ICAL (9.6°N, 78.0°E)
- Magnetic cutoff rigidities of both detectors are similar (17 GV for vertical)
- GRAPES-3 muon detector has a threshold of 1 GeV for muons. Suitable number of layers can be selected in ICAL for similar response.
- Any solar phenomena will be viewed by both detectors almost simultaneously and similar magnitude effects are expected in both detectors

GRAPES-3 Collaboration



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THANK YOU