Space Weather

Effects of Solar Transient Events on Our Planet

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Outline

- Introduction
  - Solar Cycle
  - Solar Wind
  - Solar Flares
  - CME & Shock
- Sun Earth Connection
- MFR observed by HAWC
- Transient Weakening of Earth's Msgnetic Shield
- Summarize

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  - Space Weather
  - Magnetospheric Disturbances
  - Space Weather Transients
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  - HAWC Observation
  - CME & Fluxrope
  - GCR guiding
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  - GRAPES-3 Observation
  - Simulations
  - Trajectory
- Summarize

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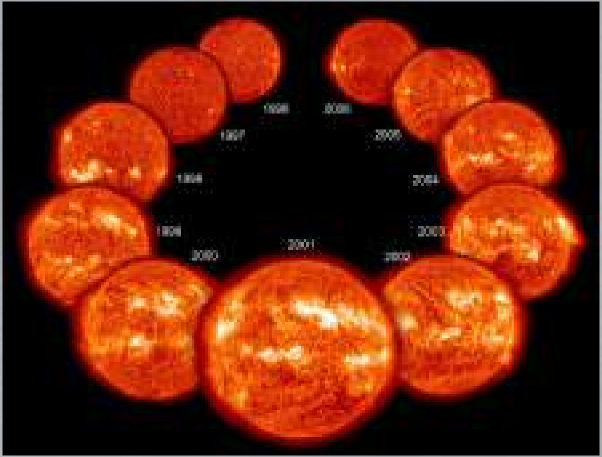

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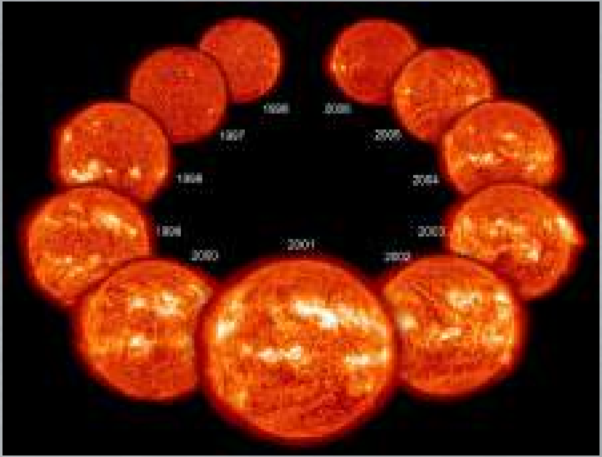

Solar Activity

- Solar wind
- Solar Flares
- Coronal Mass Ejections

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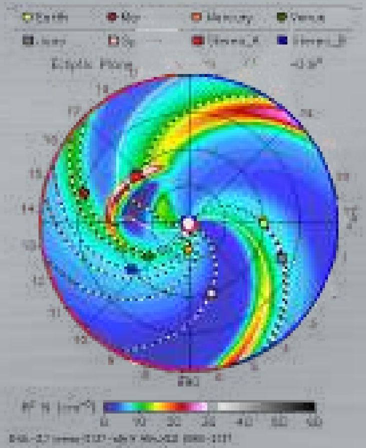
- Our Earth's magnetosphere protect us from solar wind.



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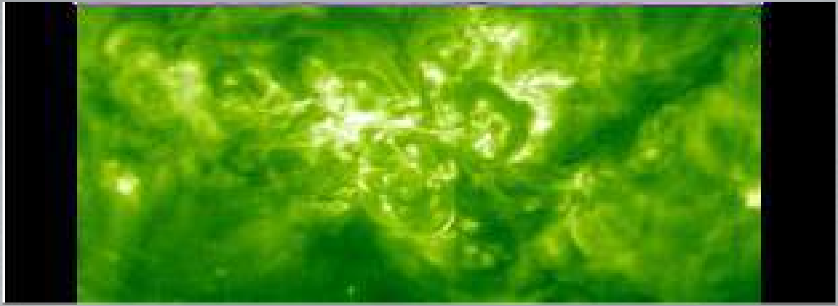
- They can produce streams of highly energetic particles in the solar wind, known as a solar proton event.



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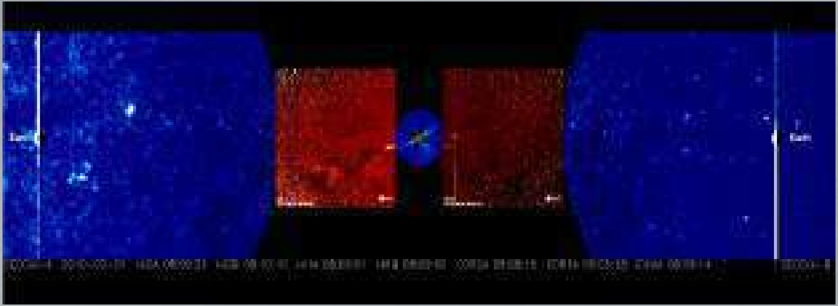
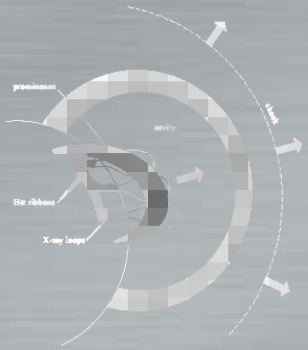
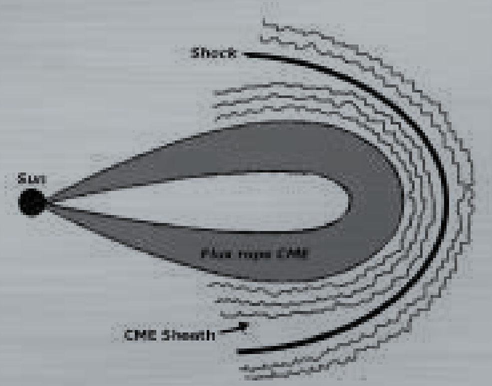


CME, Shock & Sheath





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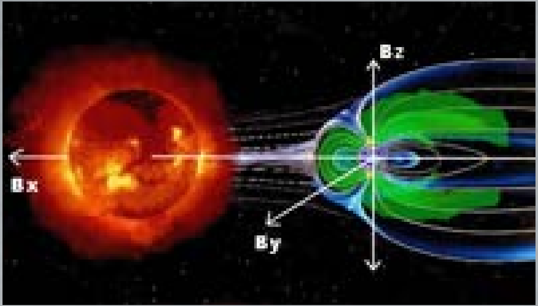
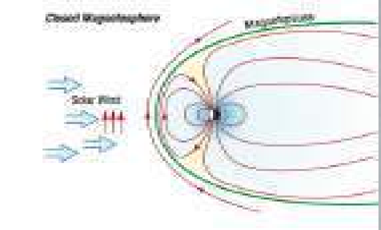
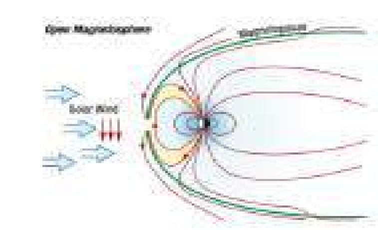
Interplanetary Magnetic fields



- B_x, is the magnetic field in the Sun-Earth line in the ecliptic plane and pointing towards Sun
- B_z, is the magnetic field parallel to the ecliptic north pole
- B_y, is the magnetic field in the ecliptic plane pointing towards dusk.

Magnetosphere disturbances





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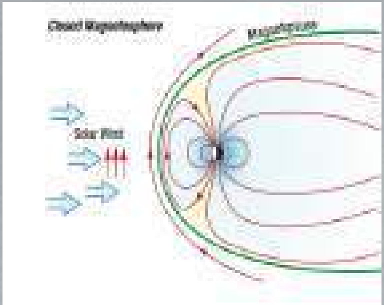
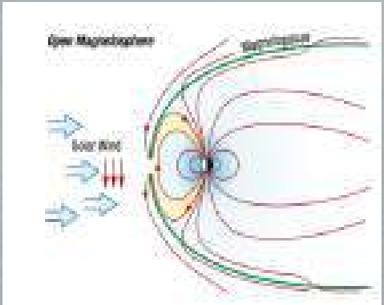
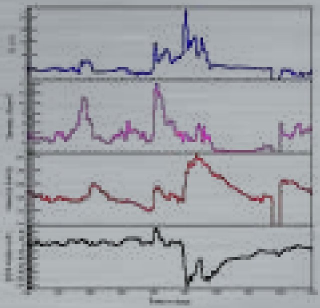




Space weather transients caused

- These transients are characterised by anomalous disturbances in all plasma parameters and changes in the magnetospheric field configuration



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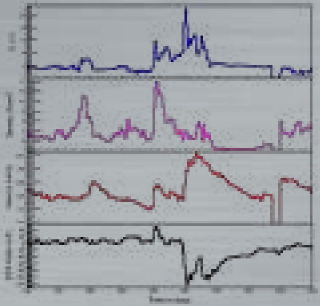

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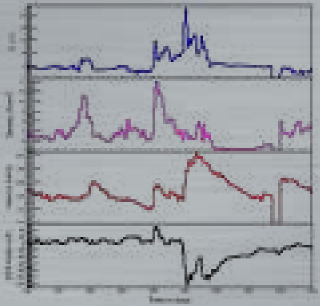

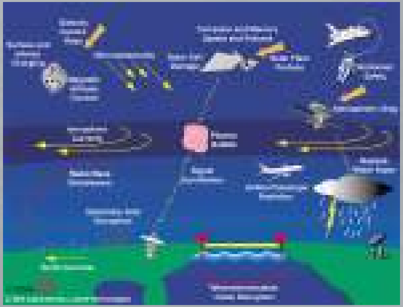

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- Historical - Carrington event Aug/Sept 1859, Nov 1882, May 1921, Aug 1972

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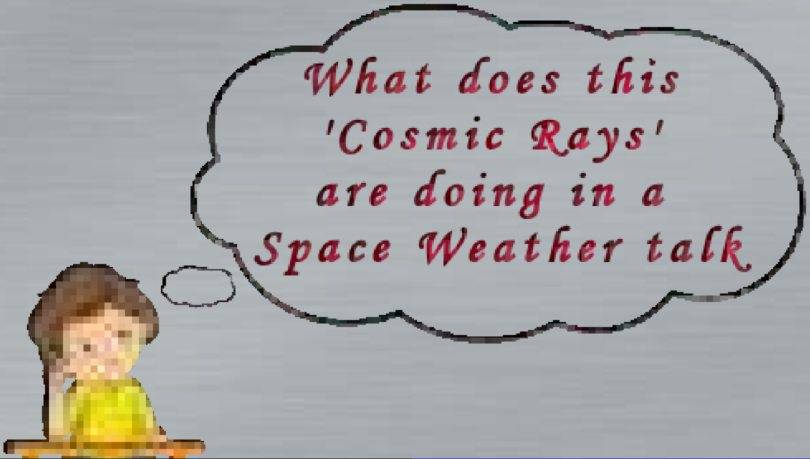
- Studying cosmic rays helps scientists understand high-energy processes in the universe and can also provide insights into the composition and behavior of interstellar matter.

Space Weather Studies



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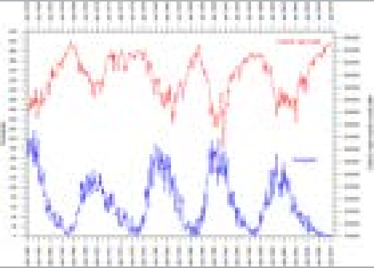
Solar Modulations of Cosmic Rays

- 11 year periodic variations
- Variations due to Sun's Rotation.
- Forbush decreases
- Solar diurnal anisotropy



- Associated with solar cycle.
- Anti-correlated with the sunspot numbers.

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- Differential rotation of Sun causes different periodicities in different latitudes.
- Depending up on position of sunspots the periodicity observed in cosmic rays may change.

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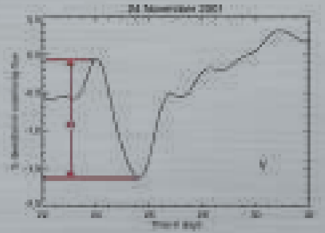

- Forbush decrease is a transient decrease in the observed galactic cosmic ray intensity.
- It is generally associated with a CME engulfing Earth.

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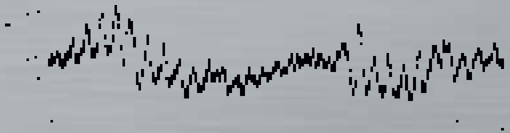

- Solar diurnal anisotrophy have periodicity ∼1 day
- Its second, third and fourth harmonics have been identified in GRAPES-3 muon data.

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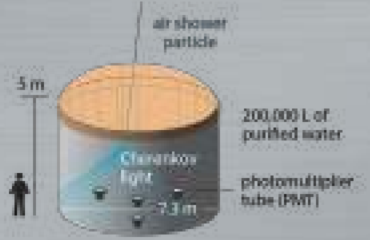
Atmospheric Modulations on Secondaries

- Pressure
- Temperature

HAWC



- Located on a plateau between Sierra Negra & Pico de Orizaba, in Mexico
- $18^{O}59'41''$N, $97^{O}18'30''$W, at an altitude of 4100 m.

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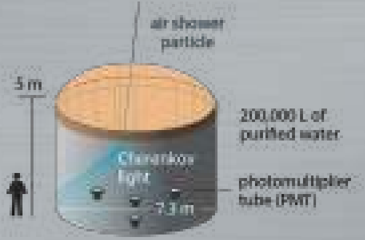

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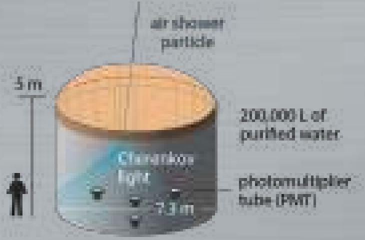

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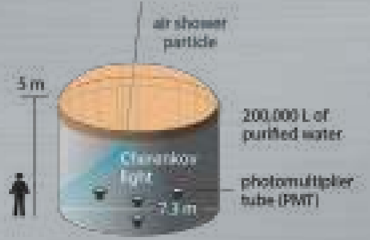

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- Single PMT rate and multiplicity M2, M3, M4 are recorded.

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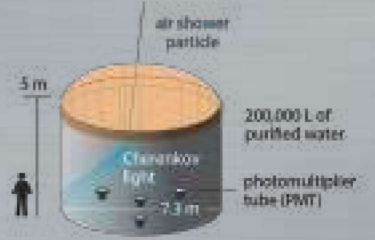

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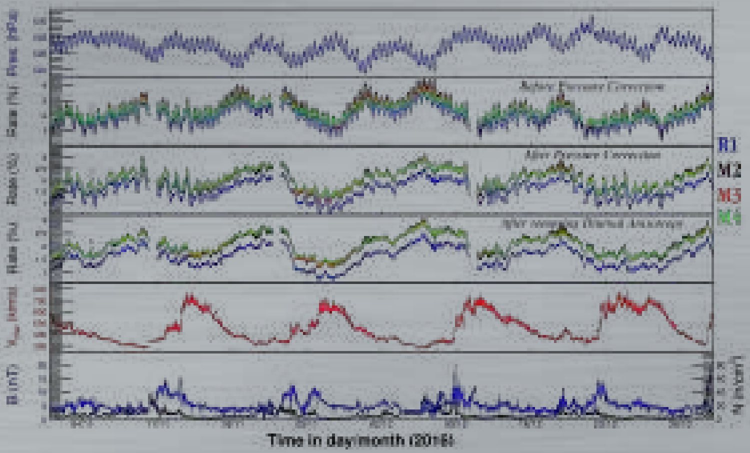
- Span over 22000 m^2 area.
- 300 Water Cherenkov detectors, Each of them 7.3 m diamter and 5 m deep.
- 4 PMTs, 10" PMT at center and 8" at equilateral triangle of side 3.2 m.
- Single PMT rate and multiplicity M2, M3, M4 are recorded.
- Cut-off rigidity 8GV and median rigidity 40-46 GV.
- Can measure GCR intensity with accuracy $< 0.01\%$ for every minute.

Corrections in HAWC



MFR observation by HAWC

Identification of a magnetic flux-rope, first time using a ground based observatory

Interplanetary Magnetic Flux Rope Observed at Ground Level by HAWC

Solar modulations

Parker's Transport equation

$$\frac{\partial n}{\partial t} + V_{SW}.\nabla n - \nabla.(\kappa.\nabla n) - \frac{1}{3}(\nabla.V_{SW})\frac{\partial n}{\partial lnP} = S$$

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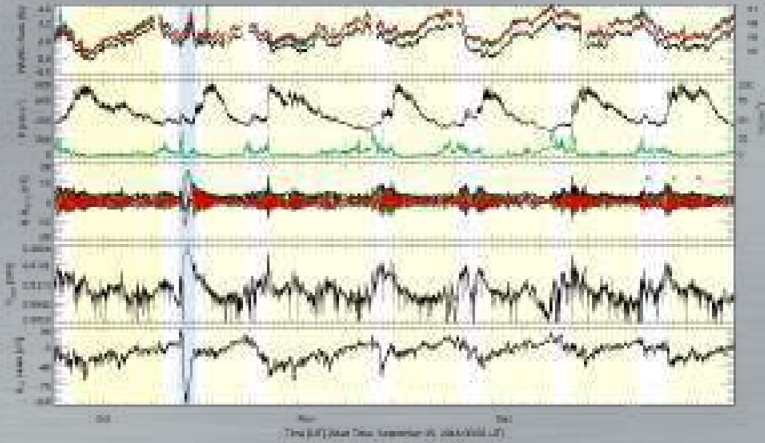
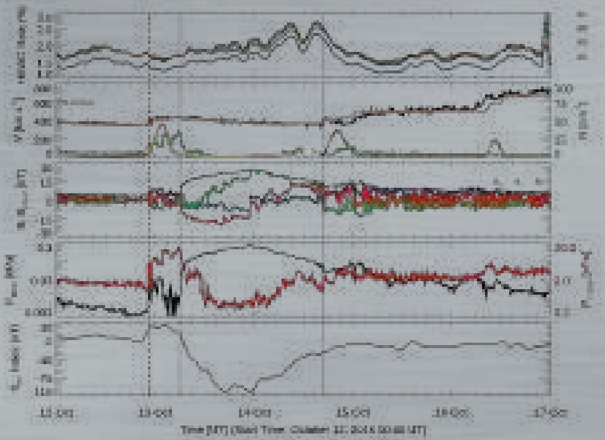
- Our observations will have modulation effects, due to variation in velocity V and magnetic field B

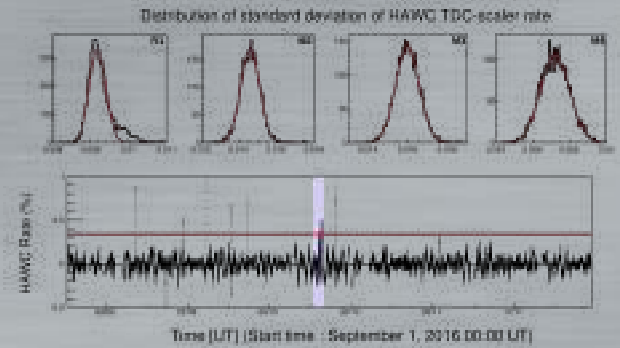
TDC Scaler Rate (Sep 25 - Dec 31, 2016)



TDC Scaler Rate (12-17 Oct, 2016)



Significance of Event in HAWC observation



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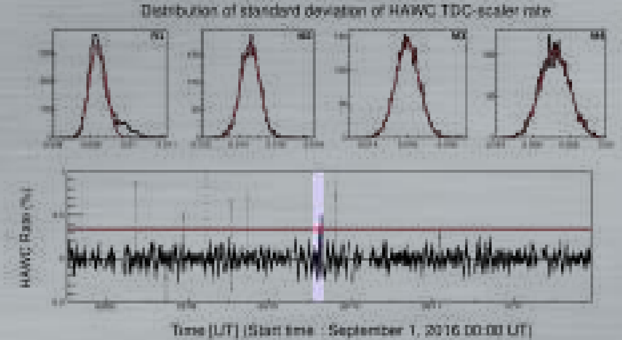
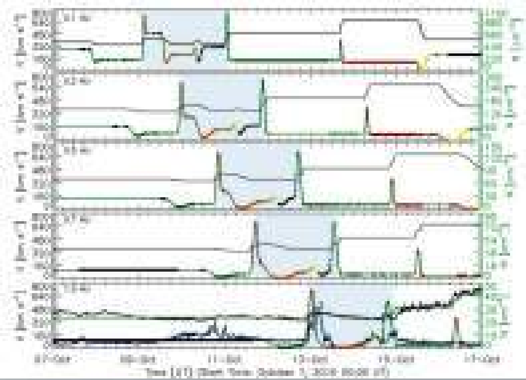


TDC-Scaler	σ (%)	Magnitude of Peak 1 (%)	Magnitude of Peak 1 in terms of σ	Magnitude of Peak 2 (%)	Magnitude of Peak 2 in terms of σ
R_1	9.18×10^{-03}	0.7122	77.6	0.7761	84.6
M_2	1.46×10^{-02}	0.7562	51.8	0.7843	53.7
M_3	1.60×10^{-02}	0.7235	45.2	0.7940	49.7
M_4	2.72×10^{-02}	0.6690	24.6	0.7570	27.8

CME transport

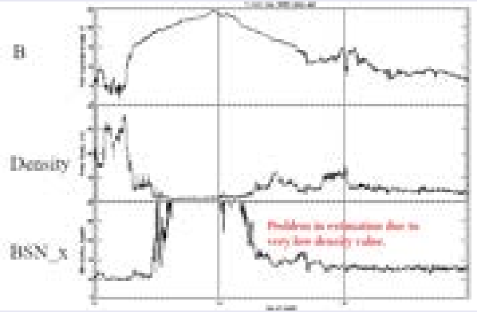
Using a 2D hydrodynamic code we are able to reproduce the speed and density SW profiles observed at 1AU before, during and after the passage of the ICME



In this particular event the CME/magnetic-cloud/flux-rope was not perturbed by other SW structures in the interplanetary medium

Effects on magnetosphere

Bow Shock Nose



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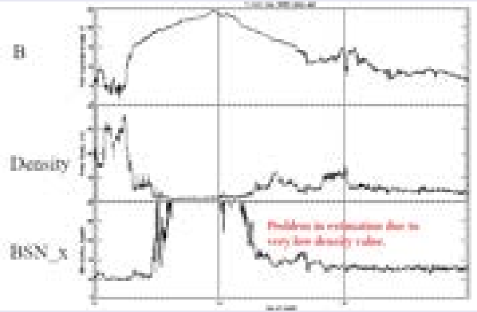
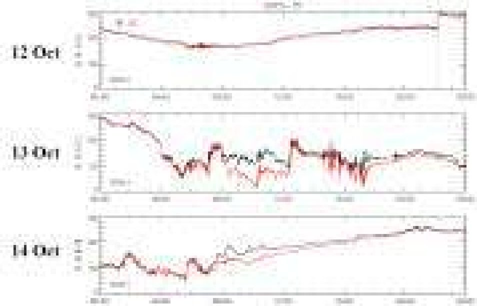


GOES data



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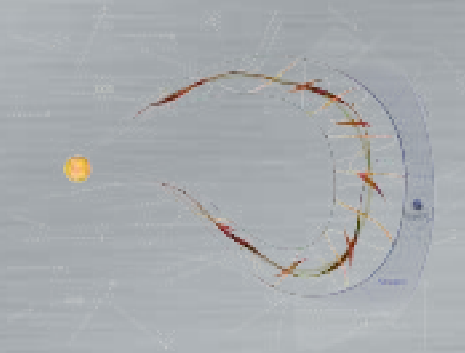

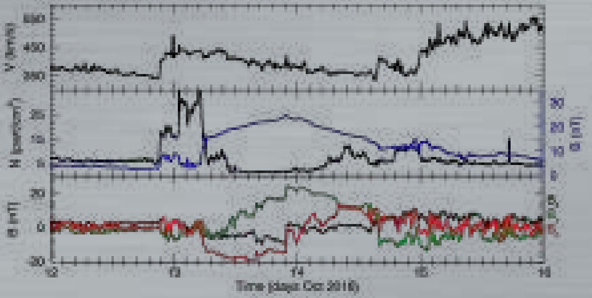

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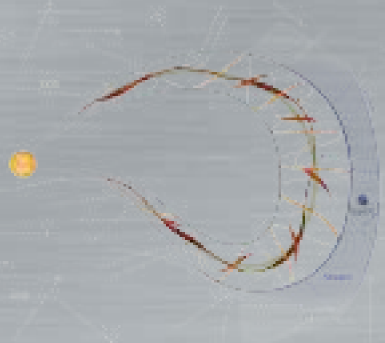

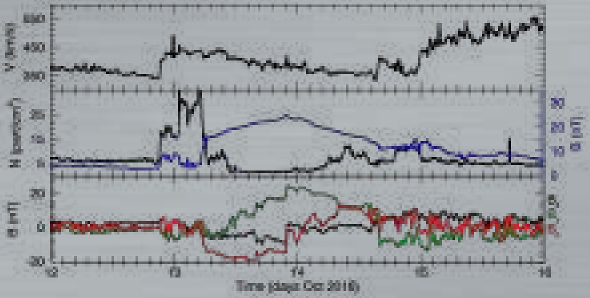

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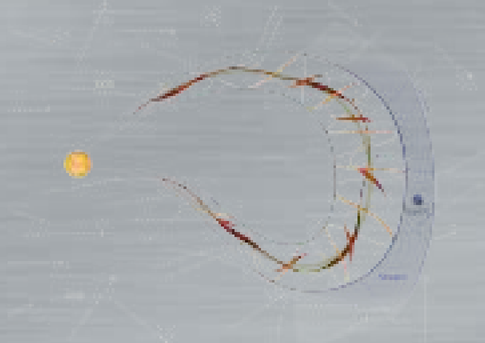

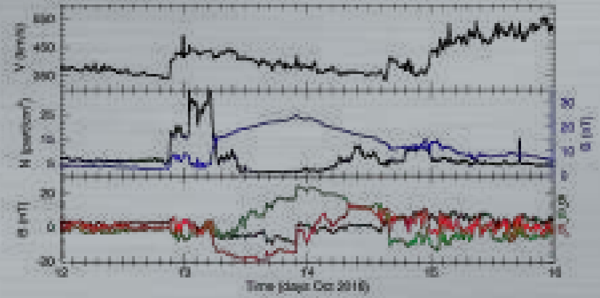

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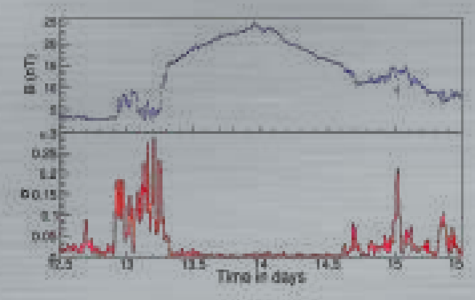
- Radius of fluxrope were 0.146 AU.

Validating GCR guiding



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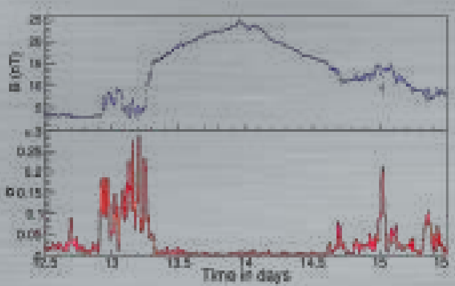

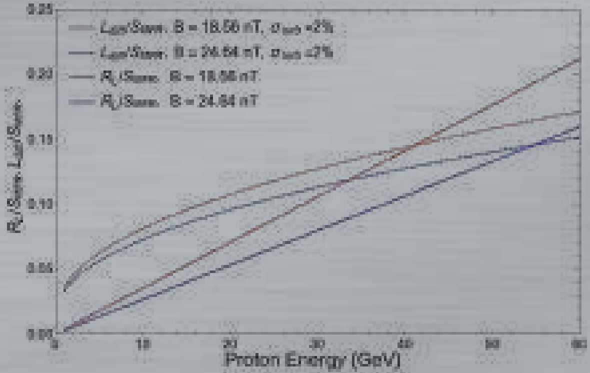

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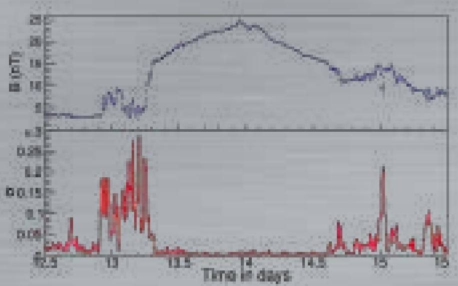

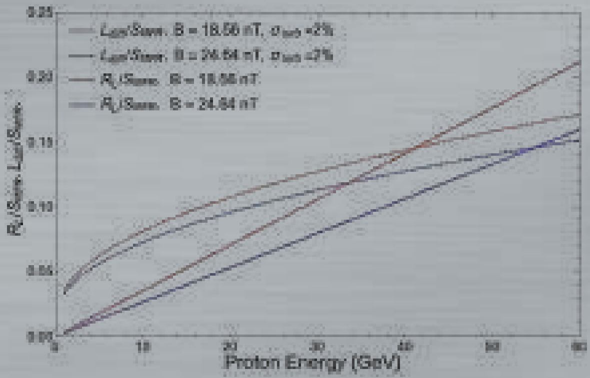

- Low turbulene level make it feasible for Lorentz acceleration.
- Larmor radius and diffusion length are $<<$ than size of MFR

Simulation of Particle Trajectory

- We used Cordinate system with origin at MFR center, which can be obtained from GSE by rotation R_Z by θ and R_Y by ϕ.

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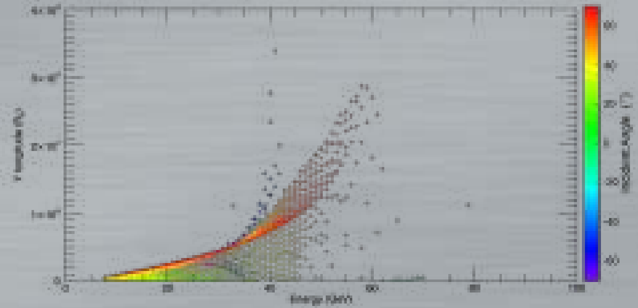
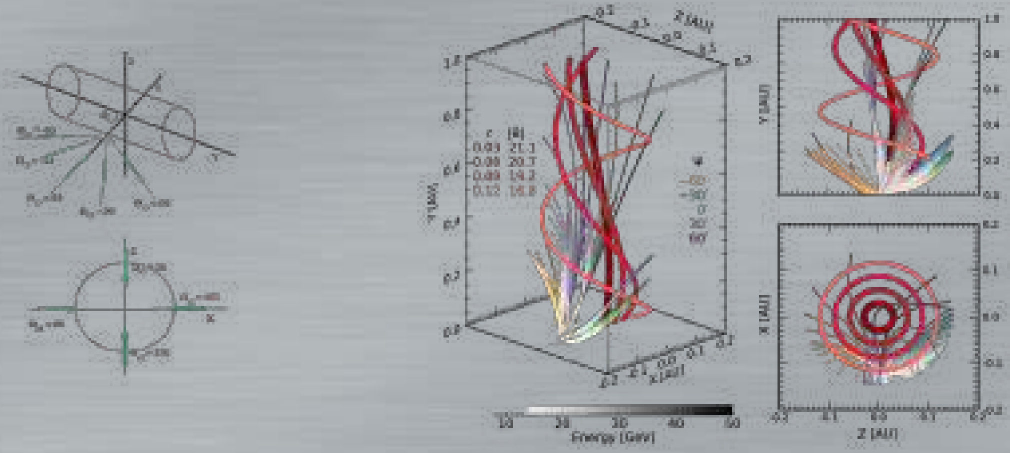
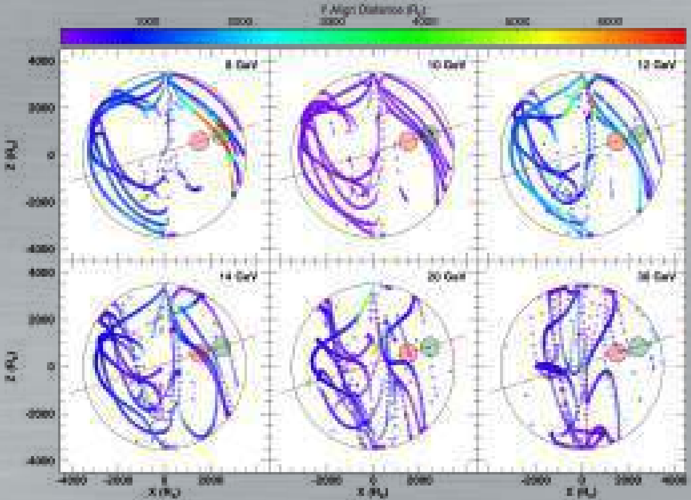


GCR guiding

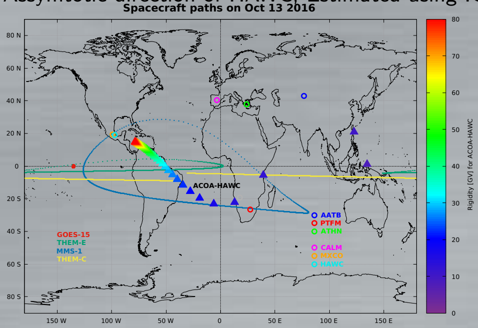


GCR guiding- Crossection view



Coupling to HAWC direction

Assymtotic direction of HAWC, Estimated using IGRF12, and backtracing method.



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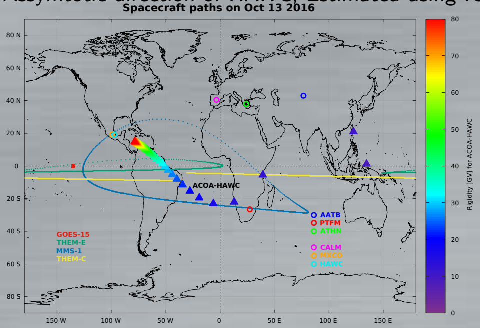

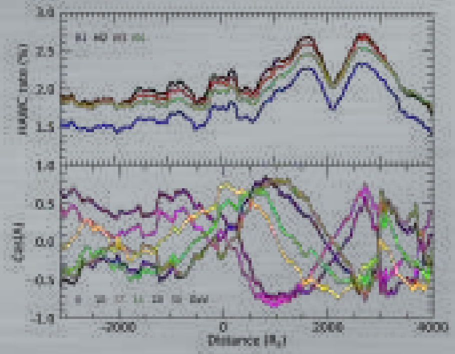

$$\cos(\Lambda) = \frac{\hat{N} \cdot \vec{B}}{|B|}.$$

Λ is the angle between assymtotic direction and the interplanetary magnetic field.

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- First evidence of particle guiding inside a fluxrope.

"Interplanetary Flux-rope observed at ground level by HAWC", S.Akiyama et al., 2020, *The Astrophysical Journal*, 905, 73.

Space Weather Studies

First ever observation

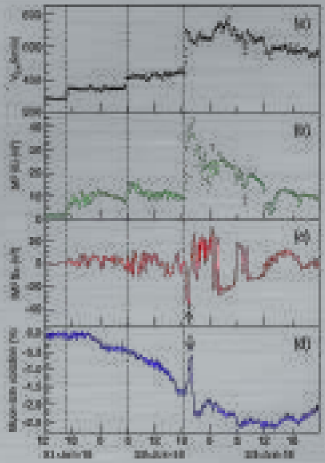
High Attention Score compared to outputs of the same age (99th percentile)

GRAPES-3

GRAPES-3

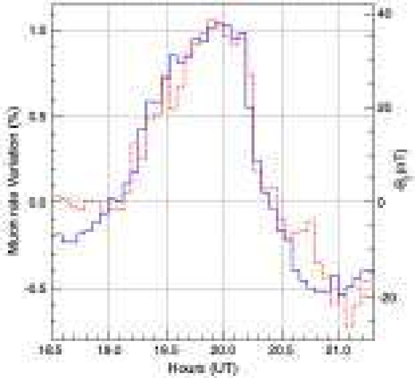
- PRC ($10\,cm \times 10\,cm \times 600\,cm$) is basic element
- 3712 proportional counters
- 4 muon stations each contain 4 modules
- Total area 560 m^2
- Energy Threshold $sec\Theta \times 1\,GeV$
- FOV is 2.3 Sr in 169 directions.

Observation



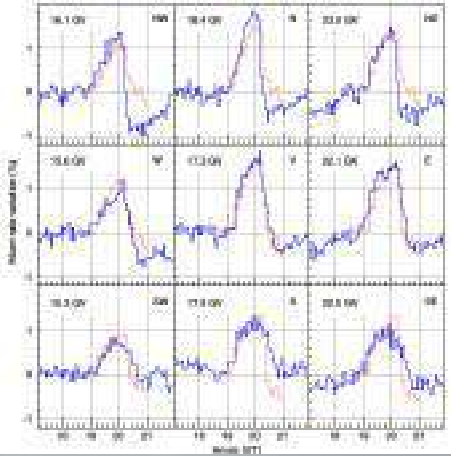
- 3 CMEs reached Earth (21 June 2015 16:45, 22 June 2015 05:45 and 18:40)
- 3^{rd} CME was faster and magnetically stronger.
- B_z component of the sheath region of this CME was peaked to ∼ - 40 nT.
- Start of Forbush decrease was observed in GRAPES-3 ∼ 4.5 hours after the arrival of first CME.
- In the midst of this FD, a 2 h muon burst (19:00–21:00 UT) correlated with B z is clearly observed.

Correlations with B_z



- Another FFT based filter was used and the muon data now contain only frequencies $\geq$ 3.5 cpd.
- The muon rate, and $-B_z$, data which was delayed by 32 mins to maximized its correlation with the muon data to -0.94%.
- Every 4 min, $\sim 10^6$ muons are detected in each of the nine directions, resulting in a statistical error of $\sim$ 0.1%.
- An excess of 9.2×10^5 on a background of 2.9×10^8 muons during this 2 h interval implies a significance in excess of 50σ.

Observations and Simulation



- We recalculate the R_c for a GMF perturbed by IMF.

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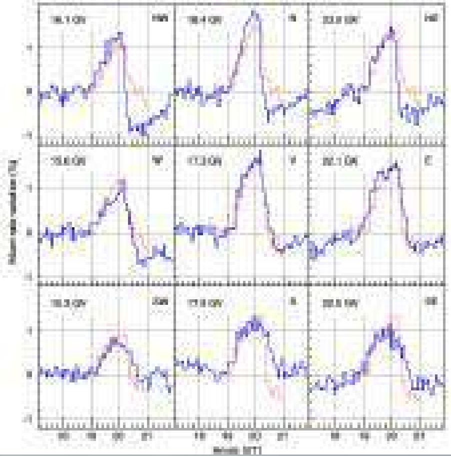

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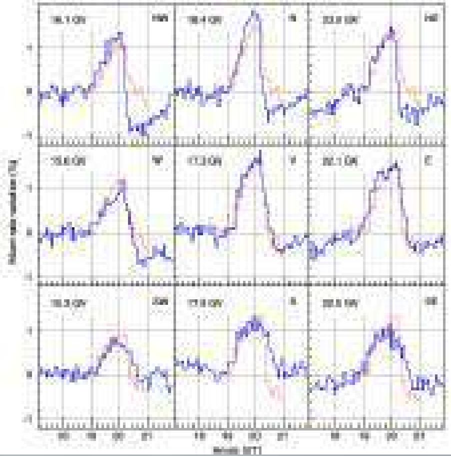

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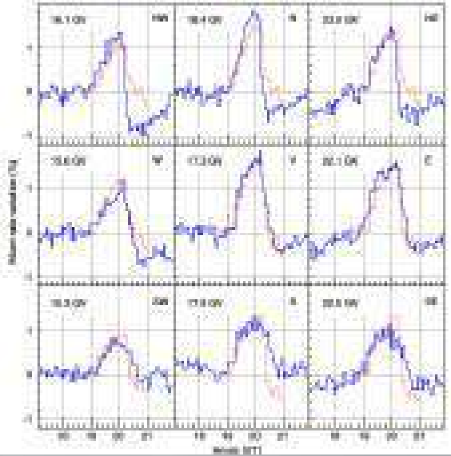

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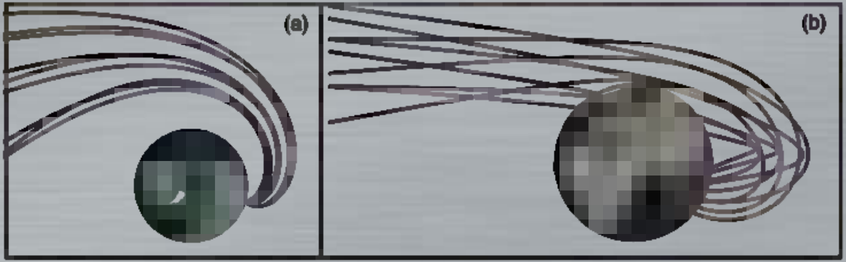
- The difference between muon rates before and after adding the IMF perturbations were calculated.
- Simulations were repeated by enhancing IMF by factor of $2 < f < 20$ and a simultanous χ^2 minimisations for 9 directions of observed and simulated profiles yield the factor $f = 17$.
- $f = 17$ implies that the B_z get enhanced to a value of - 680 nT.

Trajectory

- GCRs near cutoff rigidity experiences large deflections in GMF.
- Asymptotic directions were calculated for 5×10^4 protons of rigidities from R_c to $R_c + \delta R_c$ for every direction.
- δR_c were the changes in the respective cutoff rigidities (0.5 - 0.7 GV).
- These trajectories are bending $195^\circ - 230^\circ$; thus, the asymptotic directions lie in the opposite hemisphere.



Discussions

- The frozen-in IMF could be enhanced by the compression of CME-sheath region.
- During the event the bow-shock nose was compressed from 11.4 to 4.6 R_E.
- The implied reduction in area suggest that the B_z would have enhance by a factor of 6.14.
- Assuming the CME shock to be quasiperpendicular, it could further enhance B_z to a maximum of factor 4.
- Thus the reduction of 680 nT possibly induce by reconnection with GMF was $\sim$ 70% of its maximum possible value.
- The event was observed by the detectors in the night side, where as no significant increase was observed in detector in day side.
- The near simultaneity of the burst in all nine directions indicates its origin close to Earth.
- This burst allowed observation of the annihilation of the magnetic field arising from reconnection in a large volume surrounding Earth by the novel probe of GCRs.


Thank You..