Measurements of solar diurnal ansiotropy with GRAPES-3 experiment

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Abstract

Harmonics in the cosmic ray solar diurnal anisotropy up to third have been experimentally observed. Very high statistics is required to investigate higher harmonics because of exceedingly small amplitudes. The GRAPES-3 experiment located in Ooty, India contains a large area (560 m^2) tracking muon telescope that provides a high statistical record of muon flux ($\sim$4$\times 10^9$ per day). This allows measurement of tiny variations in cosmic ray intensity ($\lesssim$0.01%) caused by various solar phenomena. After making appropriate corrections for the efficiency of the detector and atmospheric pressure variations, a continuous stream of one year data was used to investigate the diurnal anisotropy. A fast Fourier transform based analysis revealed clear presence of the first three harmonics as well as the fourth harmonic for the first time. Further, a clear rigidity dependence of each of the four harmonics was also obtained.

Introduction

After correcting for the atmospheric pressure variations, the flux of secondary cosmic ray (CR) particles such as neutrons or muons recorded by the ground based cosmic ray detectors exhibits a periodic variation related to a solar day. This phenomena which is referred as solar diurnal anisotropy is generally explained by convection of particles outward by solar wind and diffusion along the interplanetary magnetic field (IMF). The balance of these two effects produces a net anisotropic flow of galactic cosmic rays. Detector fixed in the rotating Earth when views the flow direction, a maximum intensity is observed while a minimum intensity is observed in the opposite direction [1]. Quantitative information on solar modulation parameters such as scattering mean free path and diffusion coefficients can be obtained using parameters of diurnal anisotropy such amplitude, phase and rigidity dependences [2]. Besides a 24 h period, observations have established the existence of higher harmonics up to third [3, 4].

The GRAPES-3 Tracking Muon Telescope

A large area (560 m^2) tracking muon telescope is associated with the GRAPES-3 extensive air shower (EAS) array which is located at Ooty in India (11.4°N, 76.7°E, 2200 m altitude). The array is comprised of $\sim$400 plastic scintillator detectors of area 1 m^2 each at inter-detector separations of 8 m in a hexagonal configuration. A picture of the array is shown in Figure 1. The detection of muon component in EAS by the muon telescope based on the trigger generated by the scintillator array is used to differentiate γ-rays from charged CRs to study multi-TeV γ-ray astronomy and primary CRs based on their mass to study elemental composition around the knee of CR spectrum. The directional measurements of muon flux allow to study various solar phenomena. The details of the muon telescope are given below.

- Basic elements: Proportional counters (PRC)
- Dimensions of each PRC: 6 m×0.1 m×0.1 m
- Filled gas: P10
- Number of modules = 16
- Area of each module = 35 m^2
- PRCs per module = 58 × 4 layers
- Energy of detected muons > 1 GeV
- Number of directional bins = 13 × 13
- Field of view (FOV) = 2.3 Sr
- Observation time = 24 × 7
- muon rate per module: $\sim$ 3000 Hz
- Statistics: $\sim$4 × 10^9 muons/day

Figure 1 : View of the GRAPES-3 experimental site at Ooty with the scintillator detector array, control room building (center) and muon detector buildings (left).

Figure 2 : Inside view of one of the four muon detector halls.

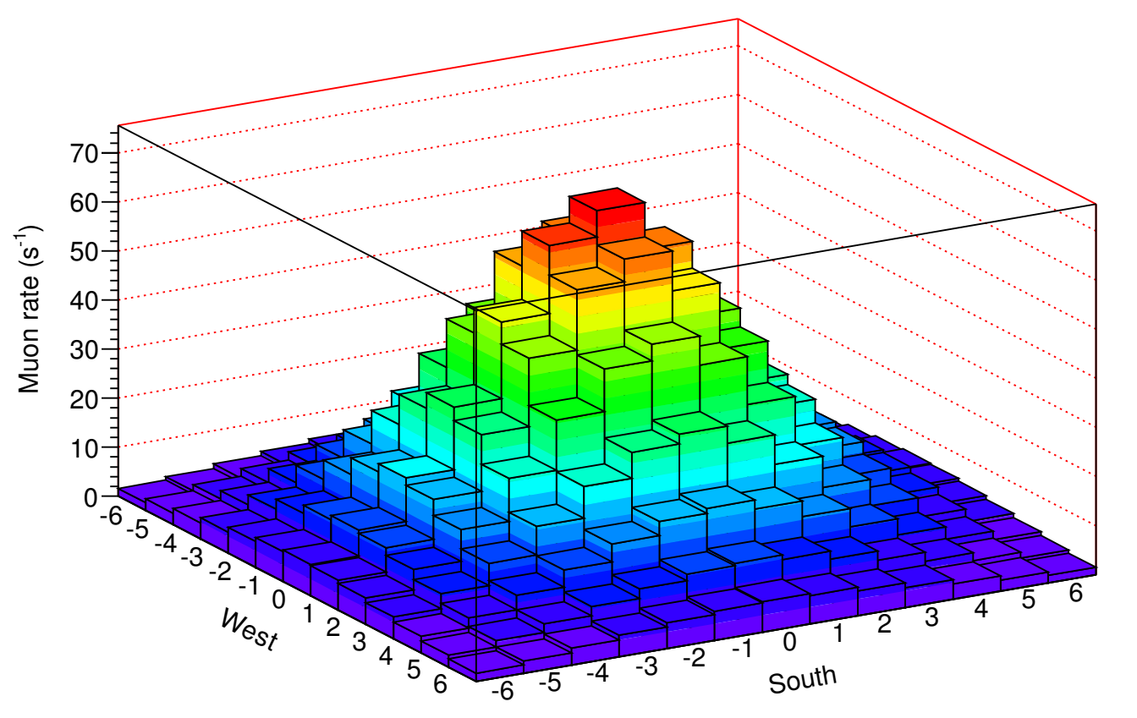

Figure 3 : Angular distribution of muons in 13×13 directional bins in the field of view of the muon telescope.

Harmonic Analysis

After correcting for various instrumental effects and the atmospheric pressure variations, the time series muons rates (4 min average) combining from the 16 modules from 1 January to 31 December 2006 were used for this analysis. Fast Fourier transform (FFT) was performed on the times series muon rates after taking percent deviations from the yearly mean, separately for the 169 directional bins. Figure 4 shows the FFT spectrum for the vertical directional bin. Harmonic peaks of the diurnal anisotropy at frequencies 1, 2, 3 and 4 cycles per day (cpd) can be clearly observed in the FFT spectrum.

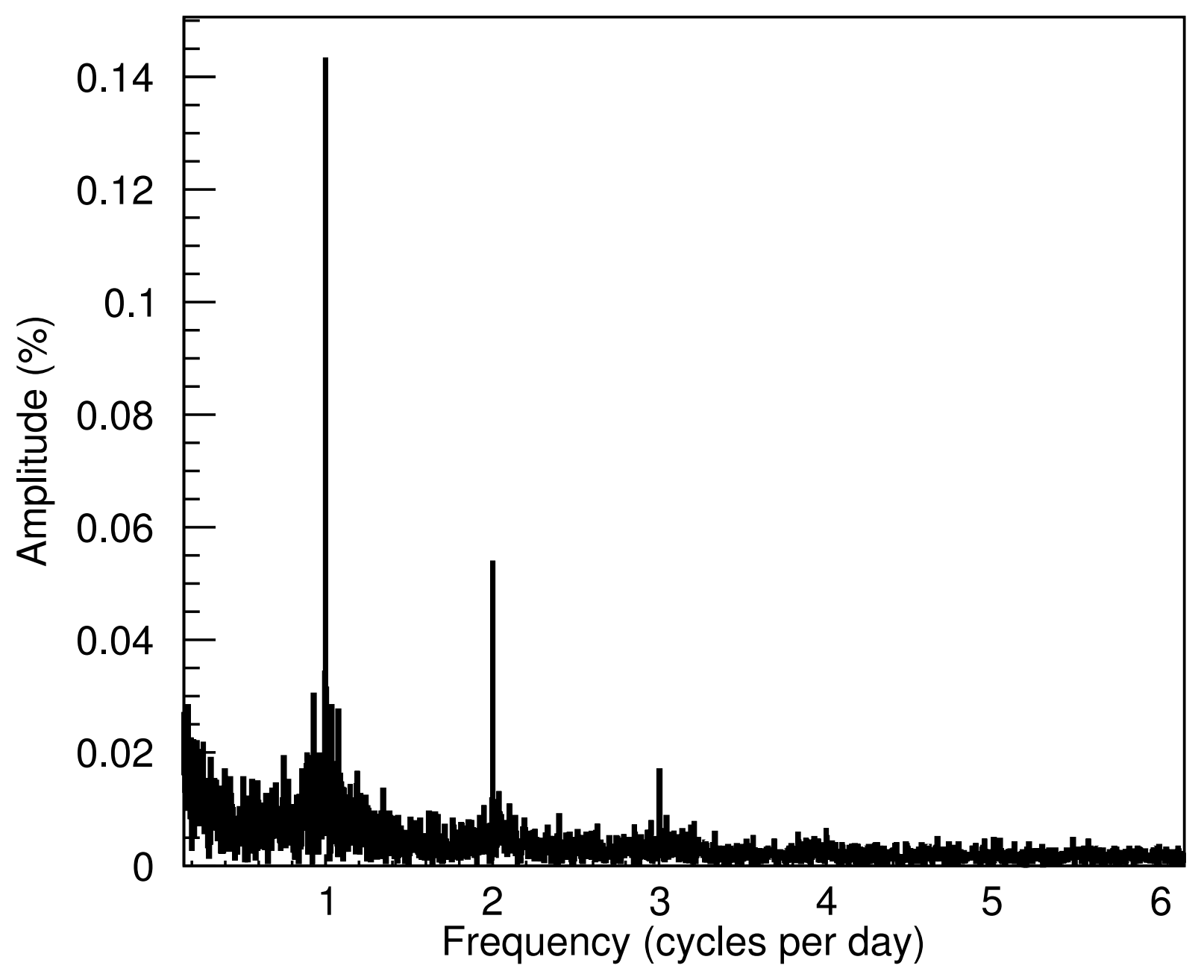

Figure 4 : FFT spectrum of muon data for the vertical directional bin of the GRAPES-3 muon detector.

Rigidity spectra of harmonics

Prior to obtaining the rigidity spectra of harmonic amplitudes, the median rigidity of the primary cosmic rays responsible for the production of muons detected in each direction of the GRAPES-3 muon telescope were calculated taking into account the effect of geomagnetic bending using a trajectory program [5] and the standard geomagnetic field model called the International Geomagnetic Reference Field 11th generation (IGRF-11) [6]. Atmospheric simulation of primary protons were performed using air shower simulation code CORSIKA [7]. An in-house developed program was used to simulate the muon detector response taking into the geometrical factors and various experimental conditions. The calculated median rigidity values varied from 64 GV to 141 GV across the 169 directional bins.

Data of 169 directional bins were combined into appropriate rigidity bins after correcting for the time offsets related to the Earth's rotation and subjected to FFT analysis. Figure 5 shows the rigidity spectra for the four harmonics. The rigidity dependence of the amplitudes were derived by fitting a power law of the form K × R_m^γ, where R_m^γ was the median rigidity and γ the spectral index. The spectral indices obtained from the fits for the first, second, third, and fourth harmonics are (-0.531±0.006), (-0.45±0.02), (-1.89±0.08), and (-1.8±0.4), respectively.

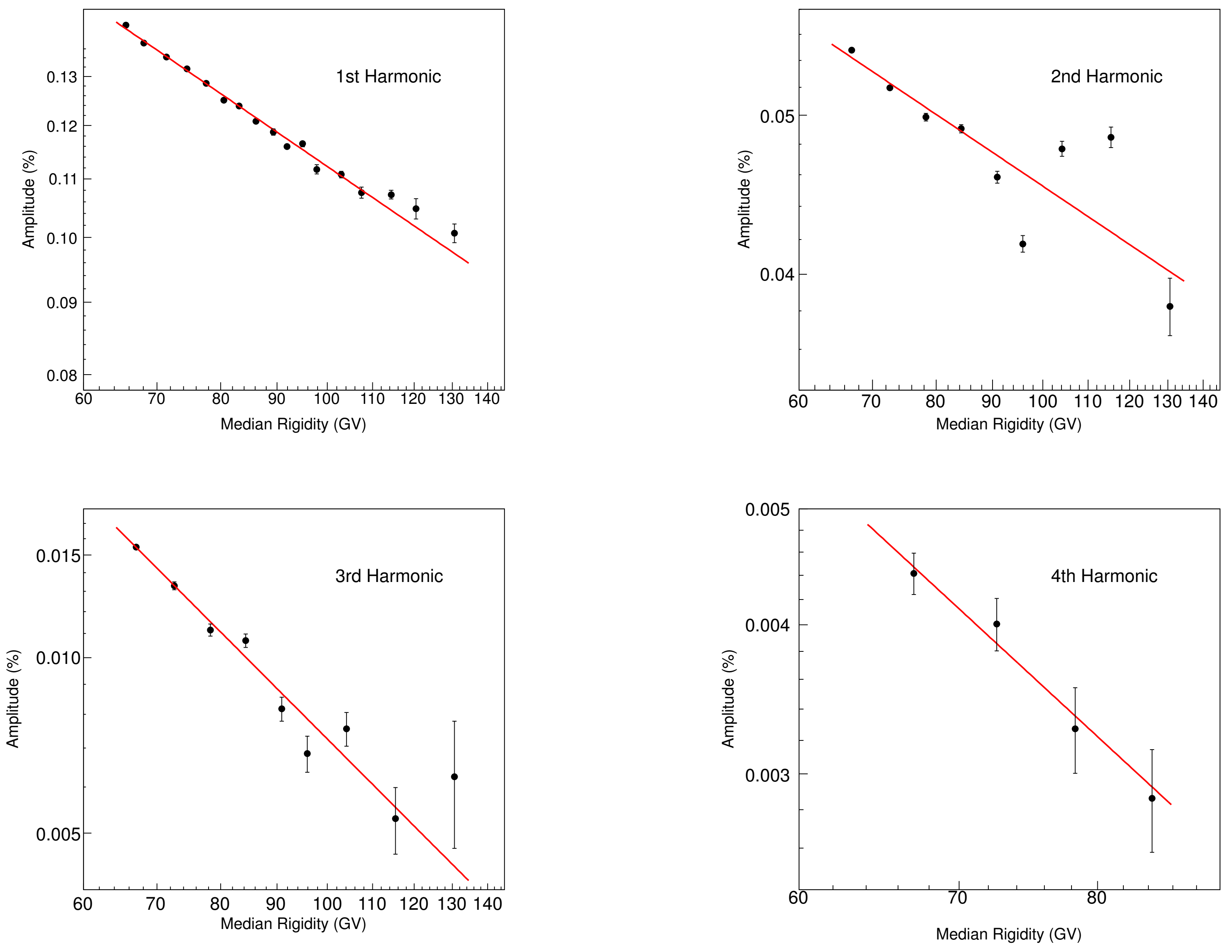

Figure 5 : Rigidity spectra of harmonics of diurnal anisotropy. Both x and y axis are shown in log scales. Red solid lines show power law fit of form K × R_m^γ, where R_m^γ is the median rigidity and γ is the spectral index.

Phase of Harmonics

The mean and the root mean square (rms) values of the phases obtained for various rigidity bins for the first, second, third, and fourth harmonics are (12.4±0.3 h), (0.4±0.3 h), (4.7±0.2 h) and (0.9±0.2 h) local time, respectively. It is interesting to note that the phases of four harmonics became nearly same if integral multiples of periods, namely, 12 h, 8 h and 2×6 h are added to the second, third, and fourth harmonic. The phase values became (12.4±0.3 h), (12.7±0.2 h) and (12.9±0.2 h) in close agreement with the phase of first harmonic.

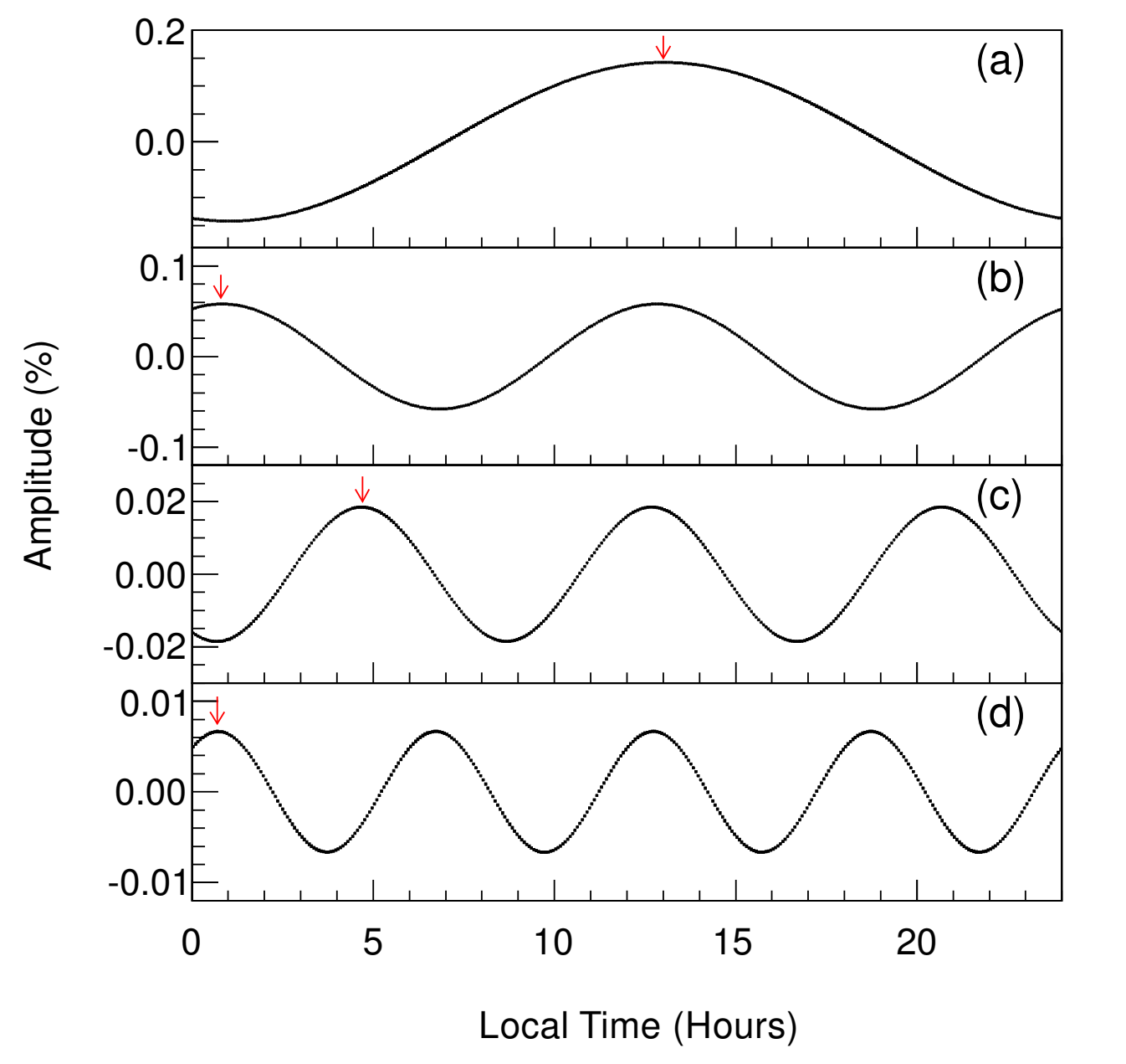

Figure 6 : Time domain data after IFFT, folded modulo 24 h for rigidity bin 64 – 70 GV, (a) first (b) second (c) third, and (d) fourth harmonic. Phase of each harmonic corresponded to the local time of first maximum indicated by pointers.

Summary

A comparison of the amplitudes of the first three harmonics from our observations provided good agreement with the results reported by others in the past. Further, the unambiguous observation of a fourth harmonic is new. The rigidity spectrum of harmonics over a wide range of rigidities with extremely high significance was measured using a single detector, namely, GRAPES-3. The observation of similar phase for all the four harmonics show that these features could not be due to different physical processes. Our results support the unified model proposed by Bieber & Pomerantz [8] that allow generation of harmonics beyond second and the higher harmonics are believed to be manifestation of a common physical process.

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