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Fast Fourier transform to measure pressure coefficient of muons in the GRAPES-3 experiment

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ABSTRACT

The GRAPES-3 large area (560 m^2) tracking muon telescope is operating at Ooty in India since 2001. It records 4×10^9 muons of energy ≥ 1 GeV every day. These high statistics data have enabled extremely sensitive measurements of solar phenomena, including the solar anisotropies, Forbush decreases, coronal mass ejections etc. to be made. However, prior to such studies, the variation in observed muon rate caused by changes in atmospheric pressure needs to be corrected. Traditionally, the pressure coefficient (β) for the muon rate was derived from the observed data. But the influence of various solar effects makes the measurement of β somewhat difficult. In the present work, a different approach to circumvent this difficulty was used to measure β, almost independent of the solar activity. This approach exploits a small amplitude (~1 hPa) periodic (12 h) variation of atmospheric pressure at Ooty that introduces a synchronous variation in the muon rate. By using the fast Fourier transform technique the spectral power distributions at 12 h from the atmospheric pressure, and muon rate were used to measure β. The value of pressure coefficient was found to be $\beta = (-0.128 \pm 0.005)\%\ \text{hPa}^{-1}$.

1. Introduction

The variation in the intensity of galactic cosmic rays (GCRs) serves as an effective probe of the space weather by studying the transient solar phenomena such as the solar flares, coronal holes, Sun spot activity, coronal mass ejections (CMEs) that produce shocks in the interplanetary medium resulting in Forbush decreases (FDs), precursors, and ground-level enhancements (GLEs) [1]. The Sun is also known to produce several periodic effects including the solar diurnal anisotropy, 27 d solar rotation, 11 y solar cycle, and the 22 y solar magnetic cycle [2,3], and these phenomena are also known to influence the space weather. The ground-based detectors are designed to observe these Sun-induced phenomena through the variation in the flux of secondary particles that are produced in the interactions of GCRs in the atmosphere. Up to an energy of 100 GeV, the primary driver for these variations in the GCR are the solar phenomena listed above.

The GCRs incident on the atmosphere interact with the nuclei in its upper layers, producing an ever increasing flux of secondary particles as they propagate downwards [4]. The secondary neutrons are produced through hadronic interactions of primary GCRs with the nuclei in the air. Due to their relatively long lifetime (~15 min), a good fraction of these neutrons survive down to the ground-level. The secondary particles in the upper atmosphere also contain mesons (pions, and kaons), and the decays of mesons result in the production of muons. A large fraction of the muons survive down to the ground-level due to an energy-loss mechanism dominated by ionization. The muons constitute the dominant component of the secondary cosmic rays at the sea-level. A large fraction of the muons are produced higher up in the atmosphere at heights of $\gtrsim$ 10 km, and suffer an energy loss of ~2 GeV before reaching the ground-level. The muon energy spectrum, and angular distribution may be derived by folding the production spectrum with the energy losses in the atmosphere, and

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by accounting for their decays. The mean energy of muons at the sea level is ~4 GeV, and their energy spectrum is flat up to 1 GeV which gradually steepens at higher energies. The integral flux of > 1 GeV muons at the sea-level is ~70 $m^{-2}s^{-1}sr^{-1}$ [5] that increases slowly at higher altitudes. The angular distribution of muons along a zenith direction 'θ' varies as $\cos^2(\theta)$ at GeV energies [6,7].

The bulk of muons detected at the ground-level are produced by GCRs of energy <100 GeV that are modulated by the solar energetic particles, and their associated magnetic fields. Consequently, the muon flux is also modulated by these solar phenomena, and displays a 24 h periodicity due to the rotation of the Earth. However, at low-Earth latitudes the measured muon flux at the ground-level including the data from the GRAPES-3 experiment [8] display a dominant 12 h periodicity, in addition to a much weaker 24 h periodicity. The 12 h period is caused by the thermal heating of the upper atmosphere by the Sun that combines with upward eddy conduction of heat from the ground generating internal gravity waves in the atmosphere primarily at these periods. These waves cause regular oscillations in atmospheric wind, temperature, and pressure fields, that were historically termed "atmospheric tides". However, this heating results in a non-linear response of the atmosphere with the occurrence of a dominant 12 h oscillation in pressure in the near-equatorial regions with an amplitude of ~1 hPa that rapidly decreases at higher latitudes. This in turn results in a synchronous variation of the muon flux with the same period. In this context, it is relevant to recollect that the phenomenon of atmospheric tides was postulated as well as actively studied since the time of Newton, and Laplace. But still it took over two centuries for a comprehensive understanding of this complex, and delicate phenomenon to emerge [9,10].

The time variation of GCRs has been studied for over seven decades with the initial studies establishing the central role of the Sun in influencing the GCR modulations [11]. The primary probes for time variation studies of the GCRs were either the secondary neutrons [12] or the secondary muons [13]. These two components provide complementary information on the GCR variation. Both the neutron, and the muon components serve as good proxies for the intensity of the GCRs. However, as mentioned above the variation in atmospheric properties complicates the interpretation of the measurements from neutron monitors, and muon detectors. Therefore, before proceeding with the analysis of data, it is imperative to understand the impact of the atmospheric parameters on the measured fluxes. Neutron monitors generally probe the GCR variations at relatively low-energies of a few GeV. On the other hand, the muon detectors are sensitive to the variations at comparatively higher energies (≳10 GeV) [12–14].

The analysis of muon data presents a greater challenge because correction for variations in both the pressure, and the temperature have to be implemented [13]. The muons are produced in the upper layers of the atmosphere through decays of mesons. A change in local temperature modifies the atmospheric density, and that in turn affects the balance between two competing processes of decays, and hadronic interactions of the mesons. For example, an increase in the upper atmospheric temperature reduces its density by expansion, and thereby increases the decay probability of mesons relative to interactions, causing a net increase in the muon flux. However, a less dense atmosphere also increases the probability of muon decays, and thereby reducing their flux. Thus, these two processes of decays of mesons, and muons work against each other, and result in temperature coefficients of opposite polarity. The outcome of this competition can be calculated provided the density, and the temperature profile of the atmosphere at the observing site were known. In the past, a number of calculations were performed to estimate their effect on the muon flux [15]. In a recent work details of the hadronic interactions, and atmospheric profile were used to provide estimates of differential temperature coefficients for muons that seem to agree well with the observations [16].

However, unlike the GRAPES-3 experiment that detects GeV muons, the underground experiments such as the MACRO [17], MINOS [18], and the deep ice experiment the ICECUBE [19] detect muons of much higher energies of hundreds of GeV. These high-energy muons are produced near the top of the atmosphere by the decays of mesons of very high energies. Therefore, the variation in their flux is caused by the changes in the temperature of the upper most layers of the atmosphere. For ICECUBE the seasonal variation in temperature over a year is rather large due to its polar location [20]. However, due a near-equatorial (11.4°N) location the atmospheric temperature above the GRAPES-3 experiences a relatively small variation. The low-energy muons detected by the GRAPES-3 are produced over a large range of heights in the atmosphere, thus, the effect of the atmospheric temperature on the muon flux is further reduced by this averaging over the height of muon production. Consequently, in the GRAPES-3 data, the variation of the muon flux due to temperature has been ignored.

The variation in atmospheric pressure changes the mass of the air column above the detector that in turn results in a corresponding variation in the flux of secondary particles. This effect may be seen from the anti-correlation of the muon rate with the pressure. However, the measured variation in the secondary particle flux at the detector is a combined effect of the change induced by the pressure as well as the solar phenomena. Therefore, the contribution of the pressure needs to be first identified, and corrected before probing the effects of solar origin. A correction for pressure variation is made by using the pressure coefficient β that may be determined from the observed muon rate. The value of β is a function of the type, and energy of the particles as well as the cutoff rigidity at the experimental site. A review of this topic is provided in an authoritative monograph [21]. Empirically, the dependence of the muon rate on the pressure may be described by an exponential function,

$$R(P) = R(P_m)\, e^{\beta \Delta P} \tag{1}$$

where R(P) is the rate at pressure P, ΔP the deviation in pressure from its mean value P_m, and β the pressure coefficient. Typical value of β is $\sim -0.1\%\ hPa^{-1}$ for muons. Since the amplitude of the pressure variation is ~ 1 hPa, therefore, the magnitude of the second, and other higher order terms in a Taylor series expansion of the exponential function in Eq. 1 can be safely ignored. Therefore, the relation between the muon rate, and the pressure can be adequately described by the following linear relation,

$$R(P) = R(P_m)(1 + \beta \Delta P) \tag{2}$$

However, such a linear approximation would not be appropriate in the case of the neutron component because the value of $\beta = -0.7\%\ hPa^{-1}$ is comparable to ΔP. Although, the expression in Eq. (2) is rather simple, however, to determine β, a number of difficulties are encountered due to the presence of a significant variation of solar origin in the GCR flux. The solar diurnal anisotropy is a major factor that interferes with this correlation depending on their relative phases. It is to be noted that the amplitude of the solar diurnal anisotropy is comparable, and during high solar activity even larger than the one induced by the pressure variation. The transient phenomena such as the FDs or geomagnetic storms can also adversely affect the measurement of β. Therefore, to obtain a reliable estimate of β, the data from intervals of low-solar activity are selected, and the data corresponding to periods of transient events are excluded [14,22]. However, some of the solar effects on the muon component are difficult to identify, and their long-term variation can significantly affect the muon rates. Thus, it is not