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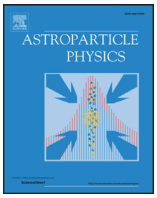

Dependence of the muon intensity on the atmospheric temperature measured by the GRAPES-3 experiment

K.P. Arunbabu[a,b], S. Ahmad[a,c], A. Chandra[a,b], S.R. Dugad[a,b], S.K. Gupta[a,b,*], B. Hariharan[a,b], Y. Hayashi[a,d], P. Jagadeesan[a,b], A. Jain[a,b], V.B. Jhansi[a,b], S. Kawakami[a,d], H. Kojima[a,e], P.K. Mohanty[a,b], S.D. Morris[a,b], P.K. Nayak[a,b], A. Oshima[a,f], B.S. Rao[a,b], L.V. Reddy[a,b], S. Shibata[a,f], K. Tanaka[a,g], M. Zuberi[a,b]

[a] GRAPES-3 Experiment, Cosmic Ray Laboratory, Raj Bhavan, Ooty 643001, India
[b] Tata Institute of Fundamental Research, Mumbai 400005, India
[c] Aligarh Muslim University, Aligarh 202002, India
[d] Graduate School of Science, Osaka City University, Osaka 558-8585, Japan
[e] Faculty of Engineering, Aichi Institute of Technology, Toyota City, Aichi 470-0392, Japan
[f] College of Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan
[g] Hiroshima City University, Asa-Minami-Ku, Hiroshima, 731-3194, Japan

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ABSTRACT

The large area (560 m^2) GRAPES-3 tracking muon telescope has been operating uninterruptedly at Ooty, India since 2001. Every day, it records 4×10^9 muons of ≥ 1 GeV with an angular resolution of $\sim 4°$. The variation of atmospheric temperature affects the rate of decay of muons produced by the galactic cosmic rays (GCRs), which in turn modulates the muon intensity. By analyzing the GRAPES-3 data of six years (2005–2010), a small (amplitude $\sim 0.2\%$) seasonal variation (1 year (Yr) period) in the intensity of muons could be measured. The effective temperature 'T_{eff}' of the upper atmosphere also displays a periodic variation with an amplitude of ~ 1 K which was responsible for the observed seasonal variation in the muon intensity. At GeV energies, the muons detected by the GRAPES-3 are expected to be anti-correlated with T_{eff}. The anti-correlation between the seasonal variation of T_{eff}, and the muon intensity was used to measure the temperature coefficient α_T by fast Fourier transform (FFT) technique. The magnitude of α_T was found to scale with the assumed attenuation length 'λ' of the hadrons in the range $\lambda = 80$–$180\ \mathrm{g\,cm^{-2}}$. However, the magnitude of the correction in the muon intensity was found to be almost independent of the value of λ used. For $\lambda = 120\ \mathrm{g\,cm^{-2}}$ the value of temperature coefficient α_T was found to be $(-0.17 \pm 0.02)\%\ \mathrm{K}^{-1}$.

1. Introduction

The variation of the galactic cosmic ray (GCR) intensity at the ground-level has been studied for over seven decades. These variations serve as an effective probe for the study of space-weather effects by the transient phenomena such as the solar flares, coronal mass ejections (CMEs), Sun spot activity, and coronal holes etc. The CMEs propagating in the interplanetary medium along with associated shocks can produce cosmic ray variations such as the Forbush decreases (FDs), precursors, and ground-level enhancements (GLEs) [1–4]. Well-known solar periodic effects such as the 27 day (d) solar rotation, 11 Yr solar cycle, and 22 Yr solar magnetic cycle, result in similar periodic response in the observed GCR intensity [5,6]. The rotation of the Earth in the ambient solar wind results in the detection of a daily modulation of the GCR intensity known as the solar diurnal variation with a period of 1 d by the ground-based instruments [7]. These instruments record the Sun induced variations in the GCR intensity through the detection of secondary particles produced in the atmosphere by GCR interactions. These solar phenomena serve as the primary drivers for GCR variations up to energies of ~ 100 GeV.

The GCRs incident on top of the atmosphere interact with the nuclei of nitrogen and oxygen, producing an increasing flux of secondary particles while propagating downwards [8]. The hadronic interactions of primary GCRs in the atmosphere are responsible for the production of the secondary neutrons. In addition,

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[*] Corresponding author at: Tata Institute of Fundamental Research, Mumbai 400005, India.

E-mail address: gupta@grapes.tifr.res.in (S.K. Gupta).

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interactions of charged particles in the atmosphere involving charge exchange, and spallation reactions may also produce neutrons. A relatively long lifetime ($\sim 15\,\mathrm{min}$) of neutrons ensures that a substantial fraction of them can reach down to the ground-level. The secondary particles in the upper atmosphere are largely mesons such as the pions, kaons etc., and their decays result in the production of muons of energies of several GeV. While traveling down in the atmosphere, muons suffer energy losses that are dominated by ionization. The muons produced high up in the atmosphere traveling along zenith angle θ, suffer an energy loss of only $\leq 2\sec(\theta)\,\mathrm{GeV}$ before reaching the ground-level. Therefore, a large fraction of the muons survive down to the ground-level. The muon energy spectrum and angular distribution can be readily obtained from the production spectrum of parent mesons along with their energy losses in the atmosphere, and by taking into account their decays. At sea-level the median energy of muons is found to be about 4 GeV with a flat energy spectrum up to 1 GeV. The muon energy spectrum becomes gradually steeper at higher energies. The total flux of $> 1\,\mathrm{GeV}$ muons at sea-level is about $70\,\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{1}$ [9]. The angular distribution of the muons varies as $\cos^2(\theta)$, where θ is zenith direction [10,11].

As explained above, the analysis of the ground-based muon flux is an effective tool for the study of various solar phenomena such as the solar diurnal anisotropy, solar flares, CMEs, and their effect on the magnetosphere of the Earth [12]. However, the analysis of the muon data requires relatively complex calculations for the atmospheric corrections due to the contributions of both the pressure, and the temperature effects. The muon intensity observed by the ground-based detectors including the GRAPES-3 displays variations correlated with the changes in the atmospheric pressure [13]. The atmospheric temperature displays a seasonal variation due to the orbital motion of the Earth around the Sun which in turn produces a seasonal change in the atmospheric density. As a consequence the muon intensity also displays a seasonal variation correlated with the atmospheric temperature. This seasonal variation was first postulated in 1952, and a fairly comprehensive phenomenological framework of its explanation was also outlined [14].

The deep underground experiments such as MACRO [15], MINOS [16], and the deep ice experiment IceCube [17] detect high-energy (hundreds of GeV) muons. These muons are produced near the top of the atmosphere by the decays of mesons of still higher energies. An increase in the atmospheric temperature causes its expansion, thereby increasing the probability of the decay of these mesons. This process results in the production of a larger number of muons. However, the muons have a negligible probability of decay due to their high energies of hundreds of GeV, and therefore, almost all of them survive to reach the deep underground location of these experiments. Therefore, the high-energy muons display a positive dependence on the temperature which was measured by the IceCube, and the MINOS detectors due to a large seasonal temperature variation ($\sim 10\,\mathrm{K}$) caused by their high latitude locations [17,18].

However, due to its near-equatorial (11.4°N) location, the atmospheric temperature above GRAPES-3 experiences a relatively small seasonal variation. The GeV muons detected by the GRAPES-3 are produced by GCRs of median energy $< 100\,\mathrm{GeV}$. The mesons (pion, kaons etc.) produced in the upper atmosphere by these GCRs typically have energies of tens of GeV. Almost all of these mesons decay in the upper atmosphere due to a relatively short decay length of $\sim 1\,\mathrm{km}$, resulting in the production of GeV muons which are detected by the GRAPES-3 telescope. Thus, any change in the atmospheric temperature has almost no impact on the decay rate of mesons. The decays of mesons in the upper atmosphere produce muons of energies of a few GeV. The energy loss of muons is $\leq 2\sec(\theta)$ for muons traveling along a zenith direction θ. This energy loss is comparable to the energy of the muons, and therefore, a sizable fraction of these muons decay before reaching the GRAPES-3 telescope. If the atmospheric temperature increases then the fraction of decaying muons also increases due to thermal expansion of the atmosphere which in turn increases the path-length traveled by the muons. As a consequence, the low-energy ($\sim$GeV) muons display a negative dependence on the temperature.

On one hand, the daily variation of atmospheric temperature affects the rate of decay of muons produced by the GCRs, which in turn modulates the intensity of the detected muons. On the other hand, the diurnal modulation of the GCRs by the magnetized solar wind also produces a daily variation in the muon intensity. Therefore, it becomes difficult to segregate the respective contributions of these two phenomena responsible for producing the daily modulation in the muon intensity. Therefore, the seasonal variation in the temperature had to be used to measure its effect on the muon intensity in the GRAPES-3 data. Due to a near-equatorial location of Ooty, the seasonal change in the atmospheric temperature was expected to be very small, and therefore, its effect on the muon intensity in the GRAPES-3 data was ignored until now.

As discussed above, the seasonal variation observed in the GRAPES-3 experiment is relatively small, specially when compared to the variation seen in other experiments which are located at high latitudes. The seasonal atmospheric temperature above Ooty varies only by $\sim 1\,\mathrm{K}$. In view of such a small variation it was important to correct for the instrumental, and atmospheric pressure effects before estimating the temperature dependence of the muon intensity. This objective was achieved by taking advantage of the high-statistics GRAPES-3 data. In the present work a unique methodology was employed to measure the temperature dependence of the muon intensity by using the GRAPES-3 data of six years collected during 2005–2010.

2. The GRAPES-3 experiment

The GRAPES-3 experiment is sited in Ooty at 11.4°N latitude, 76.7°E longitude, and 2200 m altitude in India. The GRAPES-3 consists of two main components. The first component is an extensive air shower (EAS) array of 400 plastic scintillator detectors, each with an area of $1\,\mathrm{m}^2$. These detectors are placed on a hexagonal pattern with a minimum separation of 8 m. The EAS array is used to trigger on showers of energy $\geq 10\,\mathrm{TeV}$ [19]. A large area ($560\,\mathrm{m}^2$) tracking muon telescope constitutes the second component of the experiment. The muon telescope comprises of sixteen modules each $35\,\mathrm{m}^2$ in area. It is an ideal instrument to study various phenomena at high energies caused by solar activities such as the flares, coronal holes, CMEs etc. [1–3,7,20–22]. Complementary information on an EAS provided by these two independent components has made sensitive measurements of the composition and energy spectrum of primary cosmic rays in the energy range $10^{13} - 10^{16}\,\mathrm{eV}$ possible [23,24].

The basic element in a muon telescope module is the proportional counter (PRC), which were made from a square cross-section steel tube with dimensions of $600\,\mathrm{cm} \times 10\,\mathrm{cm} \times 10\,\mathrm{cm}$, and a wall thickness of 2.3 mm. Muon modules are assemblies of PRCs placed in a four-layer configuration with consecutive layers arranged in mutually perpendicular directions as may be seen from Fig. 1. Four adjacent modules located under common concrete shielding constitute a supermodule. The cross-section of the two of these modules is visible in Fig. 1. An overburden of $550\,\mathrm{g\,cm}^{-2}$ in form of concrete blocks above the bottom most PRC layer was responsible for a threshold energy of $\sec(\theta)\,\mathrm{GeV}$ for the muons in a direction of zenith angle 'θ'. Each telescope module was instrumented to continuously record the intensity of muons in a matrix of 13×13 directions which cover a solid angle of 2.3 sr, once every 10 s.

Since each module detects muons at a rate of $\sim 3000\,\mathrm{s}^{-1}$, therefore, for the full telescope, total recorded rate of muons was