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Variation of muon counts versus solar time

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Abstract. Project GRAND observes small variations in the number of incident muons when plotted versus local solar time. The total accumulated number of muons by GRAND over four years' time is 140 billion. The data obtained by Project GRAND are compared with data from neutron monitor stations at Climax and at Newark which detect secondary neutrons. Project GRAND is an array of 64 proportional wire chamber stations which are sensitive to secondary muons at energies greater than 0.1 GeV. The mean energy of cosmic ray primaries which produce these muons depends on the spectral index. For a differential spectral index of 2.4, the most probable gamma ray primary energy is about 10 GeV, the response falling steeply below this energy and slowly above this energy (Fassò and Poirier , 2001); this most probably energy varies only slowly with spectral index.

1 Introduction

Although cosmic rays are isotropic, variations do exist. Hall et al. (1996) have shown that there is a variation expected due to co-rotation of the earth and particles in the Interplanetary Magnetic Field (IMF). As well, this anisotropy should have an amplitude of 0.6% and should be the greatest at 18:00 hours local solar time. Project GRAND uses four years of data to examine this variation with high statistics. These data are then compared with data from Climax and Newark Neutron Monitors which have a geomagnetic cut-off energy of $\sim$3 GeV..

2 Compton Getting Effect

A well known anisotropy effect is the Compton Getting effect (Compton and Getting, 1935; Cutler and Groom, 1991). The Compton-Getting effect (CGE) is caused by the motion of the detector relative to the rest frame in which the cosmic rays are produced isotropically. Equation (1) gives the magnitude of this effect:

$$\frac{\Delta\alpha(\theta)}{\alpha} = [(2+\gamma)(v_0/c)]\cos\theta \qquad (1)$$

where $\Delta(\alpha)/\alpha$ is the the fractional asymmetry. The quantity in square brackets is $[(F-A)/A]$ where F is the (forward) counting rate in the direction of the velocity and A is the average rate; cosθ gives the projection of the secondary cosmic ray along the (forward) direction of v_o, where v_o is the velocity of the detector relative to the production frame of the cosmic rays (where they are presumed to be isotropic), θ is the cosmic ray direction relative to v_0, and γ is the differential cosmic ray spectral index describing the energy spectrum of the primary cosmic ray.

Using values of 30 km/s for v_0 (the orbital speed of the Earth about the sun) and 2.7 for the spectral index, Equation (1) gives a CGE amplitude of 4.7×10^{-4} for the fractional forward-backward asymmetry caused by the revolution of the earth around the sun. The orbital speed of the Earth around the sun rather than the velocity of the sun in the Galaxy is used since the data will be analyzed in a sun-centered frame and the effect of the much larger Galactic speed will be cancelled out as the data is averaged over an integer number of years (assuming uniform data-taking over this period of time).

3 Acceptance

Project GRAND is not equally sensitive to all parts of the sky. It has a cutoff angle of 63° from zenith and it, like all ground-based detectors, has greater sensitivity to cosmic rays coming from near the zenith. In order to calculate the expected asymmetry for Project GRAND it is neccesary to use the correct data average value of $\cos\theta$ in Equation (1).

The acceptance for Project GRAND is given by $Accept$ in Equation (2). This equation is a combination of three factors, a $\cos\phi$ factor describing the projection of muons onto a horizontal surface, a $\cos^2\phi$ term which describes the

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muon absorption in the Earth's atmosphere because of inclination from the vertical direction, and two geometrical $[1 - 0.537\tan]$ factors. The angle ϕ is the angle of the muon from zenith.

$$Accept = [1 - 0.537\tan\phi_x][1 - 0.537\tan\phi_y]\cos^3\phi \quad (2)$$

The two geometrical factors of $[1 - 0.537\tan]$ arise from the use of several proportional wire planes stacked above one another. A muon which strikes the top plane but, due to its angle, does not strike the bottom plane is not counted. If a muon is coming in at a completely vertical angle, this will not occur while if it is coming in at a shallower angle it is more likely not to strike all the planes. The angle can become so shallow that there is no chance for a particle to strike all four planes; that limiting projected angle is 63° from vertical for Project GRAND. The 0.537 in the geometrical factor is the ratio of the x or y width of the detector and the vertical spacing between the top and bottom detector.

The combined acceptance function is folded with the $\cos\theta$ term from Equation (1) in order to find the asymmetry due to CGE caused by orbital velocity that Project GRAND expects to see in its counting rate. A value of 0.922 is obtained for $\cos\theta$ and this is multiplied by the CGE amplitude of 4.7×10^{-4} yielding a predicted effect of 4.3×10^{-4}.

4 Experimental Array

Project GRAND is an array of 64 proportional wire chamber stations. Each station contains four pairs of two orthogonal detector planes. Each plane consists of 80 individual detection cells. This arrangement of detectors allows for detection of the angle of a particle with a resolution of 0.25 degrees on a projected plane.

A steel absorber plate is mounted above the bottom pair of planes. A majority of muons (96%) do not interact with the plate while 96% of electrons are stopped, scattered, or shower due to the plate. In this way electron tracks can be filtered out, keeping only the muon tracks for study. The information on the arrival time and direction of each muon is written onto magnetic tape and the data archived for future analysis.

The magnetic tapes are then analyzed and a file is created containing information on the direction of origin of each muon for each complete sidereal day. The information is stored in a $1^\circ \times 1^\circ$ grid of the number of counts received in right ascension vs. declination from 1 to 360 degrees right ascension and -20 to 90 degrees declination in one degree intervals.

5 Data Analysis

Data are examined from over four years of running (January 1997 to December 2000). In that time, data on approximately 111 billion muons were taken. Each data file was tested to prevent spurious variations caused by the operation of the experiment itself (detectors malfunctioning, for example) from contaminating the data. A file for a given day was used only if the standard deviation of each degree of right ascension divided by the average counts/degree was less than 3%. Some 99 billion muons passed this test.

Next the data were converted from right ascension to solar time. This was done by shifting the individual data files in the following manner. The values for a given hour of the day come primarily from the values of the right ascension which were near zenith during that time. The amount a file's data are shifted earlier is proportional to the number of days that file is past September 23, the date when the sun is at 12 hr in right ascension. Data from September 23 are not shifted at all, while data from later in the year are shifted earlier by that fraction of 24 hours equal to the fraction of a year which the date is past September 23. This yields a result in terms of local solar time.

Once each day is shifted appropriately, the counts are summed over all declinations. In order to compare results obtained at Project GRAND with those obtained from other detectors, the local solar time based on the longitude of the respective experiment was used.

Data from the Climax Neutron Monitor in Climax, Colorado ($39.4°$N, $116.2°$W) and the Newark Neutron Monitor ($39.7°$N, $75.3°$W) are also compared (Space Physics Data System Website (2001), Newark Data Web Site (2001)). Project GRAND is located at ($41.7°$N, $86.2°$W).

6 Fits

Data from Project GRAND, Climax Neutron Monitor, and Newark Neutron Monitor are shown in Figures 1, 2, and 3, respectively. The data have been fit to Equation (1) which describes a curve with a once-per-day and a twice-per-day variation,

$$y = A + B\cos[15(x - C)] + D\cos[30(x - E)] \quad (3)$$

The B and D parameters are the amplitudes of the once and twice-per-day variation, respectively. The C and E coefficients represent the location of the peak in hours of solar time of the once-per-day and twice-per-day variation, respectively. The A parameter is the average value of the counting rate for that detector. The coefficients to Equation (1) are given in Table 1.

Table 1. Paramters of the fit coefficients in Equation (1)

Parameter	GRAND	Climax	Newark
A	1.3068×10^9	4028	3400
B	0.0025×10^9	11.3	9.34
D	0.0012×10^9	1.73	1.13
C	16.05	13.12	12.44
E	14.71	14.08	12.27

It should be noted that the Climax and Newark data represent the number of counts per hour which been been prescaled by a factor of 100 (that is, multiply these numbers by $\times 100$). Project GRAND data represent raw counts per half hour with no scaling.

7 Conclusions

The strength of the once-per-day variation is stronger than the twice-per-day variation for all three detectors. However, for the neutron monitors, it is stronger by a factor of seven or eight while for Project GRAND it is stronger by only a factor of two. This would seem to indicate that whatever is causing the twice a day variation has a greater effect on Project GRAND than on the neutron monitor stations. One problem in attempting to quantify the effect of the variation is that counting rate is dependent on the atmosphere's temperature averaged over a column of air some 15 km high, a quantity which has little relation to ground temperature and about which there are little data.

According to Hall et al. (1996) and private communication with Humble (2001) a diurnal peak in solar time is caused by cosmic rays which are trapped in (or at least partially affected by) the interplanetary solar wind, which is co-rotating with the sun. The orbital speed of these particles is about 370 km/sec faster than the orbital speed of the Earth, so they overtake the Earth causing an excess of counts in that direction.

The relative strengths of the variations are likely caused by the fact that the neutron monitors are less sensitive to the lower energy end of the primary spectrum (Humble, 2001). The expected maximum component to the anisotropy would be at 18 hrs local solar time, in free space. However, due to bending from the Earth's magnetic field, incoming particles are bent by 15 - 45 degrees so the stations' preferred direction of viewing is actually east of their physical locations. Therefore the peak should occur approximately one to three hours earlier.

Project GRAND has, however, a slightly higher primary energy cut-off due to the necessity of the primary energy to be above threshold to produce mesons which then decay to the muons which are detected by the array; these muons must have sufficient energy to traverse the $\sim$1300 g/cm^2 blanket of air above the detector. GRAND's higher primary energy cut-off would reduce the magnetic affects discussed above and predict smaller hour-of-day variations compared to surface neutron detectors which are sensitive to lower energies.

Indeed, comparing the once-a-day ratio of B/A values in Table 1, the ratios are: GRAND=0.0019, Climax=0.0028, and Newark=0.0027; thus GRAND has only 0.7 the once-a-day variations of Climax and Newark.

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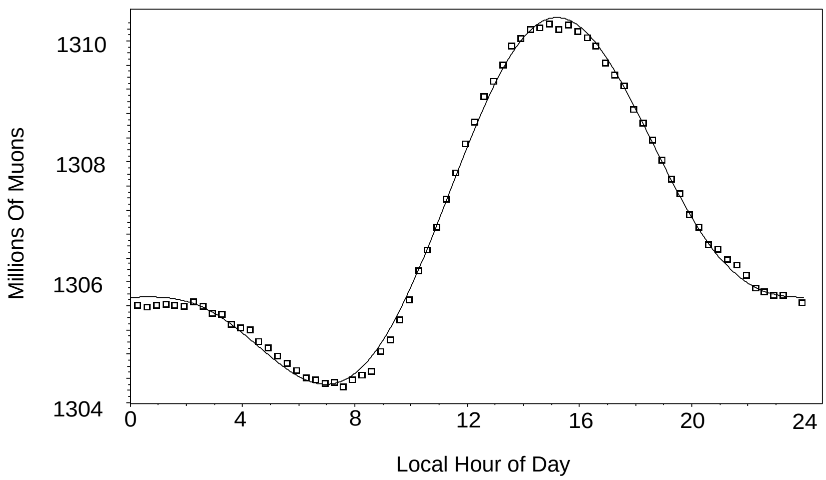

Fig. 1. Millions of muons per 20-minute interval as detected by Project GRAND versus local solar hour (GST-longitude). GRAND is located at 41.7°N, 86.2°W.

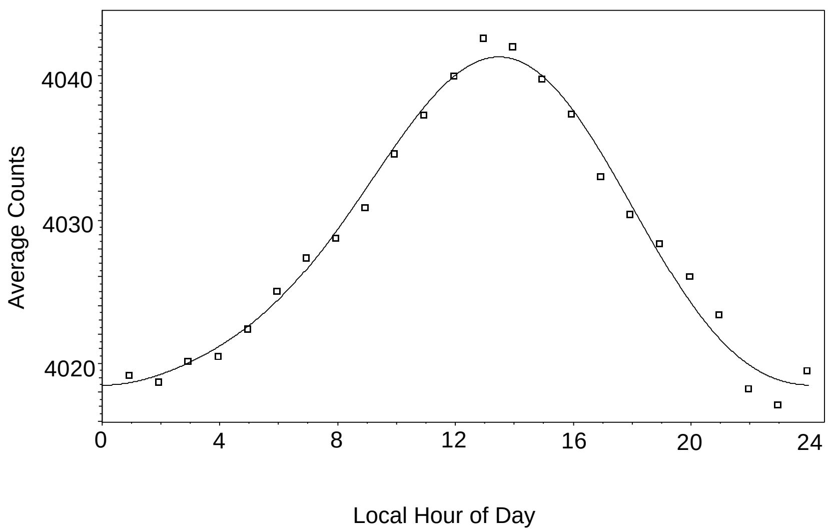

Fig. 2. Neutron counts (prescaled by a factor of 100) per hour for Climax Neutron Monitor vs. local solar time (GST-longitude). Climax is located at 39.4°N, 116.2°W.

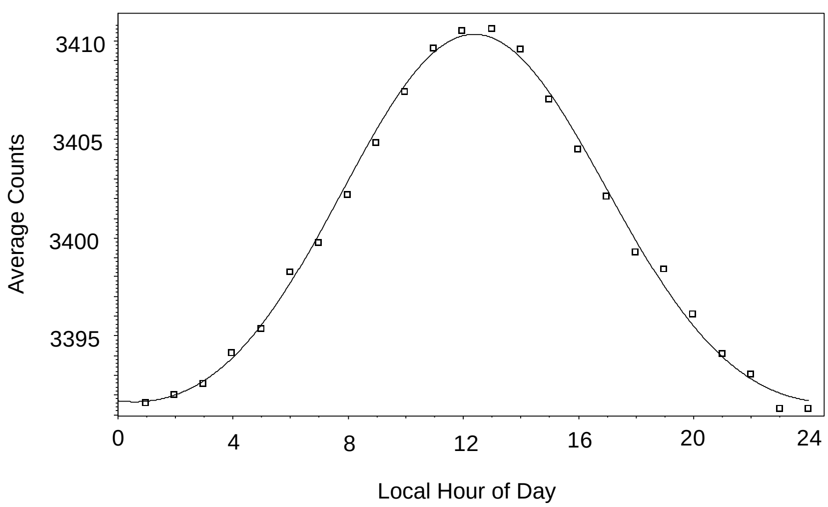

Fig. 3. Neutron counts (prescaled by a factor of 100) per hour for Newark Neutron Monitor vs. local solar time (GST-longitude). Newark is located at 39.7°N, 75.3°W.