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Influence of long term solar modulation on the relativistic muon intensity

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Abstract. During the period 1965 to 1971 a set of absolute muon intensity data available at stations having low vertical cut-off rigidities shows a small disagreement with our latitude corrected muon intensity and this could possibly be due to the maximum increase in the Zurich sun spot number which intensifies the electric tension of earth, ie the Ehmert potential. The decrease of muon intensity at around 1 GeV/c during the years 1965 to 1969 is in accord with the theoretical results calculated after O'Brien when multiplied by a factor 1·085 but lies below the theoretical values calculated after Allkofer and Dau. The decrease of muon intensity is in agreement with the Deep River integral muon intensity data during the same period.

1. Introduction

The galactic cosmic radiation is composed of 91·5 % protons, 6·5 % alpha particles and 1 % heavier particles. In general the energy spectrum of protons follows a power law of the form of about $E^{-2\cdot65}$ as is found from our previous survey (Bhattacharyya 1972) and the recent measurements of Ramaty *et al* (1973). The ground level cosmic rays differ from primary particles because of their interaction with the solar wind and the earth's atmosphere. The sun emits plasma, namely solar wind. Quenby (1965) has pointed out that the solar wind has an outer boundary where the local interstellar magnetic field strength balances the outward pressure of the solar wind. The primary galactic cosmic particles lose energy by interaction of their electrical charge with the magnetic fields of the solar wind. The variation of the sun spot number indicates the change in the solar wind velocity, and the energy loss of cosmic particles in the interplanetary medium increases with the increase of solar activity. As a result a reduced intensity of primary particles occurs in the earth's atmosphere. The solar cycles change the solar wind velocity which influences the charged particles even at a large distance from the sun. The geomagnetic field and solar wind velocity vary with time, so a change in the cosmic intensity occurs on the earth. This variation of cosmic ray intensity due to the long term solar modulation diminishes with atmospheric depth.

In the present report the long term modulation of muon intensity has been studied by using the high latitude results of Dau (1968), Allkofer and Clausen (1970), Allkofer *et al* (1970, 1971), Ashton *et al* (1972) along with the latitude corrected results of our previous work (Bhattacharyya 1970, 1974) and that of De *et al* (1972). The experimental absolute differential sea level muon intensity at about 1 GeV/c has been compared with

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the values calculated after Allkofer and Dau (1970) and O'Brien (1972). The degree of agreement of these results with the sea level Deep River integral muon monitor data determined by Steljes (1969) has also been investigated.

2. The experimental data

The experimental data found by different authors is shown in table 1.

Table 1. Experimental data.

Authors	Muon momentum (GeV/c)	Period of observation	Geomagnetic latitude	Vertical cut-off rigidities† (GV)	Absolute muon intensity ($10^{-3}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}(\mathrm{GeV}/c)^{-1}$)
Dau (1968)	1·00	Aug. to Dec. 1965	55°N	2·4	2·98±0·13
Allkofer *et al* (1970)	1·32	Jan. to Feb. 1967	55°N	2·4	2·57±0·21
Allkofer and Clausen (1970)	1·24	Nov. 1966 to March 1967	55°N	2·4	2·73±0·23
Bhattacharyya (1970, 1974)	1·00	Jan. 1969	12°N 55°N	16·5 2·4	2·15±0·16 2·67±0·19‡
Allkofer *et al* (1971)	1·11	April to June 1969	55°N	2·4	2·90±0·20
De *et al* (1972)	1·05	1972	12°N 55°N	16·5 2·4	2·47±0·41 2·97±0·48‡
Ashton *et al* (1972)	1·00	June 1972	57·5°N	2·1	3·18±0·17

† Quadratic interpolation of the world grid of rigidities after Shea and Smart (1967).
‡ Latitude corrected results after Olbert (1954).

The latitude correction for geomagnetic effects has been applied to the low latitude muon intensity data (Bhattacharyya 1970, 1974, De *et al* 1972) by using the calculated intensities after the Olbert (1954) theory for low and high latitudes. The calculated correction added for 12°N geomagnetic latitude data is $0{\cdot}52\times10^{-3}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,(\mathrm{GeV}/c)^{-1}$ at muon momentum interval $1\,\mathrm{GeV}/c$. The latitude corrected results of our investigation (Bhattacharyya 1970, 1974) along with the results of De *et al* (1972) have been presented in table 1.

The galactic cosmic radiation is, in general, influenced by the solar wind while traversing the interplanetary medium. O'Brien (1972) has pointed out that the reduction in cosmic ray beam power will be approximately proportional to the Ehmert (1959) potential and hence the ground level cosmic ray intensity will show almost a linear decrease in counting rate with the increase of Ehmert potential. Figure 1 shows the change in the Ehmert potential calculated by O'Brien (1972) from the Deep River neutron monitor data, and the Zurich sun spot number during the period 1962–1971. It is evident from figure 1 that in general the Ehmert potential lies between 200 and 700 MV from the solar minimum (1964) to the solar maximum (1969). During the same period the Zurich sun spot number changes from 7 to 120.

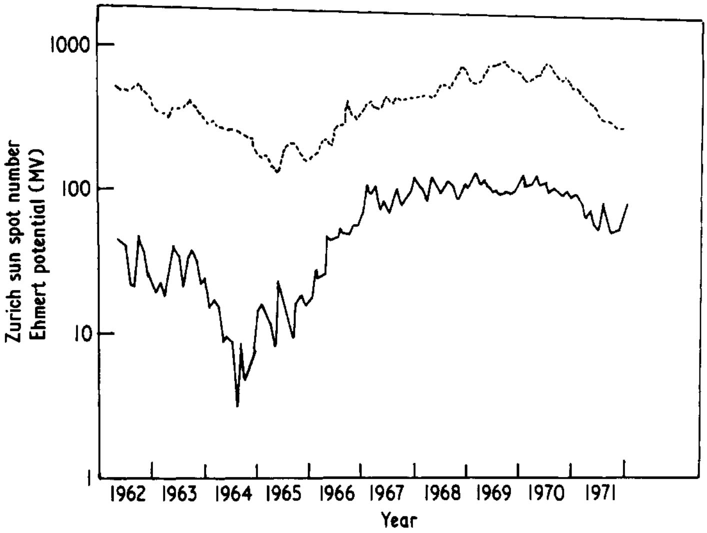

Figure 1. The Ehmert potential (MV) (broken curve) and Zurich sun spot numbers (full curve) during the period 1962–1971.

3. Theoretical aspects of long term solar modulation

The force field approximation is a solution of the Fokker–Planck equation for cosmic transport developed by Ehmert (1959), Parker (1965) and Gleeson and Axford (1967) when the radial streaming is small. The electric field model yields the magnitude of solar modulation of primary cosmic particles at the top of the atmosphere and the derived modulated galactic spectrum $N(E)$ at the earth's orbit (Ehmert 1959) follows as:

$$N(E) = N_0(T)W(T, E)$$

where

$$W(T, E) = \left(\frac{E^2+2Am_pc^2E}{T^2+2Am_pc^2T}\right)^{3/2}\left(\frac{T+Am_pc^2}{E+Am_pc^2}\right)^{-1}$$

$$T = E+ZU.$$

$N_0(T)$ is the unmodulated galactic spectrum ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}(\mathrm{GeV}/c)^{-1}$) of atomic weight A and atomic number Z having energy E MeV. U is the Ehmert potential, which is found from figure 1.

Taking the primary composite spectrum at solar minimum after Ramaty *et al* (1973) the sea level muon intensity (differential) at 1 GeV/c calculated by using the nucleonic transport code based on a phenomenological model of nucleon–nucleus collisions that is incorporated into a solution to the Boltzmann equation for hadron and muon transport (O'Brien 1971) at different solar activity has been plotted in figure 2 along with the experimental results of different authors. The theoretical value of the sea level muon intensity calculated after Allkofer and Dau (1970) has been plotted on the same figure.

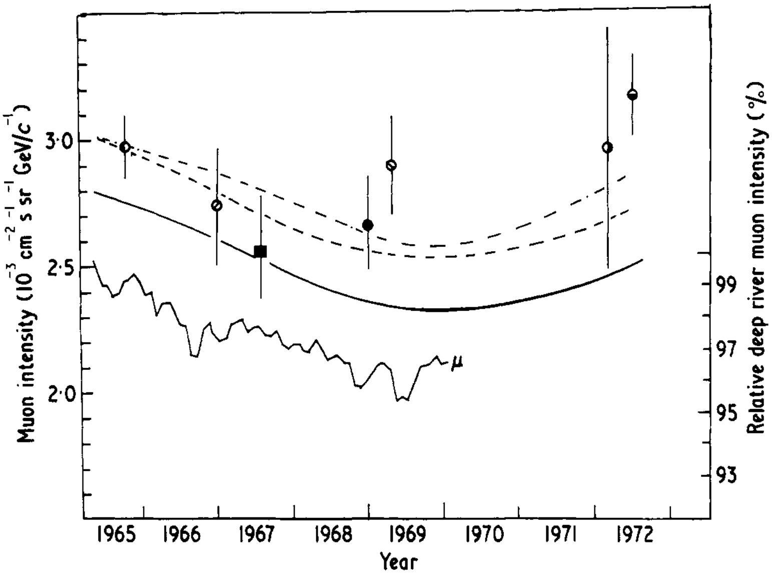

Figure 2. The sea level differential muon intensity at about 1 GeV/*c* during the years 1965–1972: Experimental data: ◐ Dau (1968), ⊘ Allkofer and Clausen (1970), ■ Allkofer *et al* (1970), ● Bhattacharyya (1970, 1974), ⦸ Allkofer *et al* (1971), ◑ De *et al* (1972), ⊖ Ashton *et al* (1972) and the theoretical values calculated after Allkofer and Dau (1970) (chain curve), and after O'Brien (1972) (full curve). Best fit: broken curve. μ: Deep River muon intensity data after Steljes (1969).

4. Discussion

The variation of muon intensity due to a change in the solar activity is small when calculated after Allkofer and Dau (1970); but it is appreciable when estimated after O'Brien. The decreasing trend in the theoretical curve in figure 2 has been observed during the change in the solar activity from 1965 to 1969 and this is supported by the spectrometer results on the absolute muon intensity around the momentum 1 GeV/*c*. The theoretical results of Allkofer and Dau lie above the experimental results of Allkofer and Clausen (1970), Allkofer *et al* (1970) and Bhattacharyya (1970, 1974). The theoretical curve after O'Brien yields a good fit with the experimental data points when the calculated intensities are multiplied by a factor of about 1·085. The range spectrometer measurements of Allkofer *et al* (1971) yield a higher intensity compared to those reported previously. The measurements after 1970 give a higher value which can be due to the decrease of sun spot number and it is supported by the theoretical results. The Deep River muon monitor data of Steljes (1969), plotted in the same figure, support the decrease in the integral muon intensity at muon momentum of 0·5 GeV/*c* or more and the decrease is about 5 % during the change in solar minimum to solar maximum.

The track visualizer measurements show a steady decrease with the increase of solar activity. The range spectrograph results of Allkofer *et al* (1971) and De *et al* (1972) have shown a higher intensity than those reported previously by Dau (1968), Allkofer and Clausen (1970), Allkofer *et al* (1970a) and Bhattacharyya (1970). This can be due to the underestimation of rejection of accompanying muon events by using Bhabha's (1935, 1938) theory. Recently Allkofer and Grupen (1970) have found that Bhabha's theory of the knock-on production yields too low a value for the knock-on electron cross section. The Bhabha theory underestimated the knock-on electron events determined by Roe and Ozaki (1959), Chaudhuri and Sinha (1965), Kearney and Hazen (1965) and Allkofer *et al* (1971a) especially in the region of electron energy transfer below 1 GeV. The bias of rejection of events accompanying muons is important since a high energy muon, after a certain energy transfer to an electron counted by the range spectrograph for its lower residual range, causes the admixture of the particles in the spectrum energy region. Moreover the coincidence method of determining absolute differential muon intensity yields an excess error due to the time variation of cosmic muon intensity and the statistical uncertainty of the counting rates. A disagreement in the experimental data is also possible due to the slight shift of muon momentum from 1 GeV/*c*.

The experimental data represented in figure 2 during the period 1965 to 1969 reveal the fact that the reduction in cosmic ray beam power is proportional to the Ehmert potential and the ground level 1 GeV/*c* muon intensity shows an approximately linear decrease with the increase of electric potential U. The cosmic ray particle loses energy due to the solar activity. The change in solar activity causes a variation in the solar wind velocity which modulates the charged cosmic ray spectrum in the Earth's orbit. The modulation is the effect of cosmic ray transport through the interplanetary medium and it is formally the same as that which would be produced by a heliocentric electric field having a magnitude at the Earth's orbit of about 200 MV at the solar minimum and about 700 MV at solar maximum (figure 1). The electric field model is a useful method for explaining the variation of cosmic ray intensity due to solar activity. The major difference in the high latitude muon intensity can be due to the solar modulation which appears by the solar wind transport of magnetic scattering centres. In any case the review in figure 2 indicates that the muon intensity has a dependence on the long term solar modulation apart from the systematic errors in the measurements around the muon momentum 1 GeV/*c*.

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