J. Astrophys. Asrt. (1985) **6,** 57–60

A Study of Solar Modulation of Medium Energy Primary Cosmic Ray Nuclei

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Received 1984 August 21; accepted 1984 December 6

Abstract. The energy spectra of primary cosmic rays were studied in the energy interval 150 to 450 MeV/nucl by using balloon-borne cellulose-nitrate solid-state plastic detector. Effects of solar modulation were studied using the theoretical spectrum of H_1 nuclei near the solar minimum in 1964 as the demodulated spectrum. The 'force-field' potential which fit the experimental results was estimated to be 270 MeV/nucl.

Key words: cosmic rays, energy spectra—cosmic rays, solar modulation

1. Introduction

The cosmic-ray nuclei suffer modulation due to the physical conditions, mainly electromagnetic, prevailing in the interplanetary space. Of the different variations, the eleven-year cycle of solar activity is of paramount significance in relating the energy spectra outside the interplanetary region to the one observed near earth. The variation of fluxes of heavy cosmic-ray nuclei during a solar cycle is observed to be small above energies of 600 MeV/nucl. In the present investigation, we have studied the solar modulation effect on heavy cosmic ray nuclei by using the 'force-field' solution (Gleeson & Axford 1968), making use of the theoretical demodulated spectrum given by Paruthi *et al.* (1976).

2. Experimental procedure

We have used a stack of Daicell cellulose-nitrate solid-state plastic detector exposed to primary cosmic-ray nuclei for 10.66 h on 1969 June 27 from Fort Churchill, Canada, at a ceiling altitude of 2.8 gm cm $^{-2}$ during the solar maximum. It may be noted that 1969–70 was a period of the polarity reversal of the Sun (Howard 1974). The details of the experimental procedure and the selection criteria are given elsewhere (Das & Goswami 1983).

3. Results and discussion

The differential fluxes of each nucleus from Ne to Fe have been estimated in the energy interval 150 MeV/nucl to 450 MeV/nucl. The differential energy spectra of

H_1 (Z =10–15) nuclei, the most abundant nuclei with $10 \leqslant Z \leqslant 26$ in cosmic rays, are plotted in Fig. 1. The differential fluxes of these nuclei in each energy interval of 50 MeV/nucl are given in Table 1.

Since the first formulation of the cosmic-ray transport equation for interplanetary region, including the effects of diffusion, convection and energy loss (Parker 1965), it has been an accepted fact that the galactic cosmic rays with energies $\leqslant$ 20 GeV/nucl propagating through the interplanetary medium lose energy due to adiabatic deceleration in the expanding magnetic irregularities. Fokker–Planck equation to be satisfied by the cosmic-ray density $U\,(r,\,T)$ is given by (Parker 1965),

$$\frac{V}{r^2}\frac{\partial}{\partial r}(r^2U)-\frac{2V}{3r}\frac{\partial}{\partial T}(\alpha TU)-\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2K\frac{\partial U}{\partial r}\right)=0 \tag{1}$$

where $U(r,\,T)$ is the differential number density of cosmic-ray particles at a radial distance r from the Sun in the kinetic energy range T and $T+\mathrm{d}T$, V is the solar wind speed, K is the diffusion coefficient and $\alpha = (T + 2E_0)/(T + E_0) = (E + E_0)\,/E$ with E_0 the rest mass energy and $E = T+E_0$, the total energy of cosmic-ray particles. The equation describing the effects of convection and scattering of cosmic-ray particles by magnetic scattering centres carried along by the radially moving solar wind is obtained with the assumption that (i) the steady-state condition prevails, (ii) the speed of solar

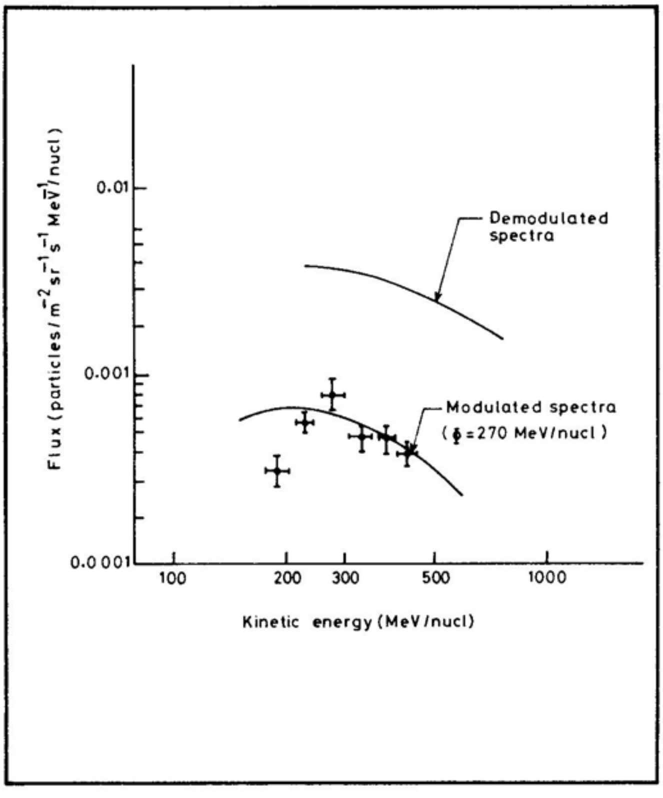

Figure 1. Differential, energy spectra for H_1 nuclei.

Table 1. Differential fluxes of $H_1(10 \leqslant Z \leqslant 15)$ nuclei.

Energy interval MeV/nucl	Fluxes 10^{-4} particles $\mathrm{m}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{MeV}^{-1}$/nucl
151–200	3.19 ± 0.23
201–250	5.89 ± 0.32
251–300	8.38 ± 0.31
301–350	4.78 ± 0.23
351–400	4.79 ± 0.41
401–450	3.90 ± 0.21

wind is spherically symmetric, and (iii) the diffusion coefficient is isotropic. Equation (1) can be solved numerically (Fisk 1971) or by an approximation method (Gleeson & Axford 1968). Gleeson & Axford (1968) showed that if the modulation is small and the diffusion coefficient is a separable function of heliocentric distance *r* and momentum *P,* then an approximate solution of Equation (1) will be

$$\frac{J(r,E)}{E^2 - E_0^2} = \frac{J(R, E+\phi)}{(E+\phi)^2 - E_0^2}. \tag{2}$$

Solution (2) is generally known as the 'force-field' solution, where $J(r,E)$ is the differential intensity of the particles of electric charge Z_e at a heliocentric distance *r* and total energy *E*, $J\ (R.E + \phi\ )$ is the corresponding intensity at the boundary of the modulating volume of radius *R* corresponding to total energy $(E + \phi)$, E_0 is the rest-mass energy of protons, and ϕ is the so-called 'force-field' potential energy. The parameter ϕ can be identified with the mean energy loss by cosmic-ray particles in penetrating the interplanetary region from the interstellar space, *i.e.* during their traversal from the boundary of modulating region into the point of observation.

The modulated near-earth spectra derived by using the numerical and force-field solutions differ from each other only at very low energies. For kinetic energies $\leqslant$200 MeV/nucl, the two solutions practically give the same result (Fisk 1971; Bhatia, Paruthi & Kainth 1977). We have used the force-field solution in deriving the near-earth modulated spectra.

To study the effects of solar modulation, the theoretical spectrum predicted by Paruthi *et al.,*(1976) for 1964 has been taken as the demodulated spectrum, as this has been found to fit well with the experimental values obtained by Webber & Ormes (1967) and by Durgaprasad & Reames (1967) in different energy intervals ranging from 180 to 3000 MeV/nucl. Using the force-field solution (2), the different energy spectra for different values of ϕ(150–300 MeV/nucl) are predicted. The curve corresponding to ϕ= 270 MeV/nucl is in better agreement with the experimental values. High-energy part of the energy spectra is seen to agree fairly well with the predicted spectra for ϕ = 270 MeV/nucl. The low-energy part indicates predominant solar modulation higher than expected from the force-field solution. The poor fit at low energies may perhaps be due to the uncertainties in the form of the unmodulated cosmic-ray spectrum outside the solar cavity.

A change in cosmic-ray flux occurs during a solar cycle due to solar activity. We have compared our data with those of 1964 (solar minimum) as obtained by Bhatia *et al.* (1967) to find the effect of solar activity on cosmic rays. The ratio J_{64}/J_{69} comes out to be nearly 3.8 indicating that the flux during the solar minimum (1964) is 3.8 times the flux during solar maximum (1969). This shows that high solar activity in some manner prohibits the galactic cosmic rays from entering the interplanetary space.

Acknowledgements

The authors are grateful to Professor S. Biswas (TIFR) forgiving the stack as a gift. The valuable comments received from Dr N. Durgaprasad (TIFR) and Dr J. N. Goswami (PRL) are also gratefully acknowledged. The financial assistance from the UGC is acknowledged. The facilities provided by the Department of Physics, GU is also acknowledged. We are grateful to Professor P. Dasgupta for going through the manuscript.

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