Solar Modulation of Galactic Electrons and Their Diffusion Coefficient in the Heliosphere

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Abstract

In the force-field approximation of solar modulation, the modulation potential Φ represents the magnitude of cosmic-ray intensity decrease. We investigate the correlations between Φ and the neutron monitor count rate N. Φ-N curve and its slope are calculated in the force-field model and compared with Φs estimated from electron experiments. Those Φs are separated into two groups of different solar polarities and the calculated curves fit them. In addition, the modulated electron spectra are calculated with various energy dependences α of the diffusion coefficient in the heliosphere. Those are sensitive to the values of α.

1. Introduction

Galactic cosmic rays, below 10GV, are especially influenced by solar modulation. The electron experiments[2] show that the intensity between solar maximum and minimum conditions varies by a factor of 6 for 1GeV electrons. The simplest modulation model, the force-field approximation, represents the magnitude of solar modulation by the potential energy ΦMeV. The recent measurements of the positron/electron ratio (e.g. [3]) suggest a charge sign dependence of solar modulation and the drift dominated model has been presented to explain the dependence. The correlations between Φ and the neutron monitor(NM) count rate N have been investigated by Badhwar et al.[1] using nuclei data. We investigate Φ-N relations for galactic cosmic electrons. Next we calculate the modulated electron spectra and study the energy dependence of the diffusion coefficient of cosmic rays in the heliosphere.

2. Force-Field Approximation of Solar Modulation

In the force-field approximation[4] the differential intensity J of galactic cosmic rays (total energy E, rest energy m) at the distance r from the sun and at the time t is given by

$$\frac{J(r,E,t)}{E^2-m^2} = \frac{J(\infty,E+\Phi)}{(E+\Phi)^2-m^2} \tag{1}$$

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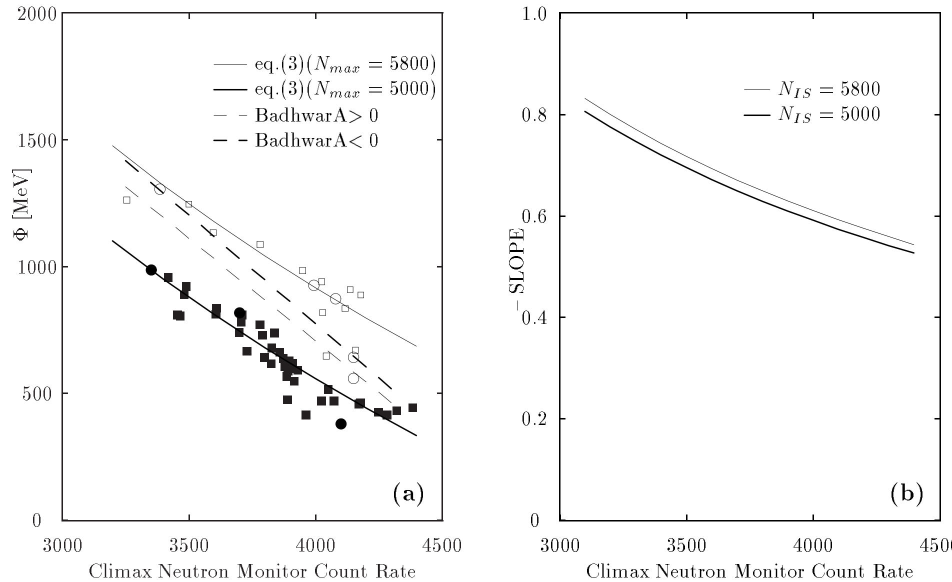

Fig. 1. (a) The correlations between the modulation energy Φ and the Climax NM count rate N_c. The symbols are values estimated from electron measurements for LIS in Fig.2(b); ICE 1.2GeV electron data[2] in 1980s A<0 (filled squares) and in 1990s A>0 (open squares), and others(circles) are measurements below 10GeV shown in Fig.2(b). The solid curves show 11GV proton curves of eq. (3) with $N_{max} = 5000, 5800$ respectively. The regression (dashed) lines of nuclei data are given by Badhwar(1996)[1]. (b) Slope of Φ-N_c curve, that is $d\Phi/dN$ in eq. (3).

where $J(\infty, E)$ means the local interstellar spectrum(LIS). The modulation function Φ is calculated from the definition, $\Phi(r, E, Z, t) = \psi(\zeta + \phi, Z, t) - \psi(\zeta, Z, t)$ with the function ζ and ϕ,

$$\zeta(E, Z, t) = \int_m^E \frac{D_2(R', t)}{(E'^2 - m^2)^{1/2}} dE', \quad \phi(r, t) = \int_r^{r_b} \frac{V(r', t)}{3D_1(r', t)} dr' \tag{2}$$

where the cosmic-ray charge Ze, the solar wind velocity V, the boundary of heliosphere r_b, and the diffusion coefficient $D = \beta D_1(r, t) D_2(R, t)$ of galactic cosmic rays ($\beta = v/c$, particle velocity v and rigidity R). It has been indicated that Φ is correlated to the neutron monitor count rate N[1] and N is approximately proportional to the proton flux of energy E_m. First we obtain the Φ-N relation from the above formulas. If LIS in a certain range is expressed in a power-law of mementum energy p, $J(\infty, E) = J_0 p^{-\gamma}$, eq. (1) yields the expression of Φ including the ratio $J(\infty, E)/J(r, E)$ at energy E, and we obtain the Φ-N relation,

$$\Phi = \{p^2 \cdot (\frac{J(\infty, E)}{J(r, E)})^{2/(\gamma+2)} + m^2\}^{1/2} - E \sim E_m \{\sqrt{(\frac{N_{max}}{N})^{2/4.7} + (\frac{0.94}{E_m})^2} - 1\}\ , \tag{3}$$

since $J(\infty, E_m)/J(r, E_m)$ of protons is approximated by the ratio N_{max}/N, where N_{max} is the NM count rate that is never influenced by solar modulation and cannot exactly be evaluated. In the case of Climax NM (N_c), $E_m = 10.7$GeV[2] and the proton spectral index $\gamma = 2.7 \pm 0.05$ around 11GV (e.g. Menn et al. 2000), and the calculated curves are shown in Fig.1(a) with N_{max} =5000(A<0), 5800(A>0). We also estimated Φ from the electron measurements using the LIS in Fig2.(b) that was estimated from the radio data in Fig2.(a). In Fig1.(a) the filled symbols represent the A<0 state and the open symbols represent the A>0. The symbols are clearly separated into two groups of different solar polarities as indicated previously[2]. The calculated curves fit the data. The slope $d\Phi/dN_c$ has the value between –0.5(solar min) and –0.8(solar max) as shown in Fig.1(b). The most important fact is that the slope is almost independent of N_{max}. And the slope has only 4% changes due to γ's uncertainty. Since $E \gg \Phi$ in the solar minimum period, Eq. (3) becomes the simpler result, $\Phi \simeq E/(\gamma+2) \cdot \ln(J(\infty, E)/J(r, E))$. The slope $-E_m/(\gamma+2)/N_c$ is independent of N_{max}. The difference between the drift model and the force-field model appears in the solar minimum period. If the drift dominates, N_c little changes and Φ changes largely in A>0 state, so that the slope of Φ-N_c should be steeper than the value in Fig.2(b) and be flatter in A<0 state. Namely, in Fig.1(a), the time trajectory of the ICE observation is expected to move vertically in A>0 and horizontally in A<0, in the large N region.

3. Propagation of Galactic Electrons in the Heliosphere

The diffusion coefficient of galactic cosmic rays in the heliosphere is currently not known well. In this section we investigate how that energy dependence apears in the galactic electron spectrum. If we put $D_2(R,t)/1\mathrm{GV} = (p/1\mathrm{GeV})^\alpha$ and $a = m/p$, eq. (2) becomes $\zeta/1\mathrm{GV} = (p/1\mathrm{GeV})^\alpha \cdot f(p)$, where

$$f(p) = \int_0^1 x^\alpha/(x^2+a^2)^{1/2}dx = \frac{1}{a}\frac{1}{(1+\alpha)}F(\frac{1}{2}, \frac{\alpha+1}{2}, \frac{\alpha+3}{2}; -\frac{1}{a^2})$$

(F:the Gauss hypergeometric function). Since galactic electrons always satisfy $p \gg m$ ($a \ll 1$), we expand the above function to second term and get the sufficiently accurate expression,

$$\zeta/1\mathrm{GV} = (p/1\mathrm{GeV})^\alpha(\ 1/\alpha + C(\alpha)a^\alpha + O(a^2)\ ) = \frac{D_2(p)}{\alpha} + C(\alpha)\cdot m^\alpha + O(p^{\alpha-2})$$

where $C(\alpha) = 1/2 \cdot B((\alpha+1)/2, -\alpha/2)$ (B : beta function). The approximation gives the value of ζ within the error of 0.01% and the parameter is given by

$$\Phi = \{((\frac{D_2(p)+\alpha\phi}{1\mathrm{GV}})^{1/\alpha}\cdot 1\mathrm{GeV})^2 + m^2\}^{1/2} - E\ ,$$

where if $m = 0$ and $\phi/\zeta \sim \alpha\phi/p^\alpha << 1$, the familiar expression $\Phi = (p/D_2)\phi$ is obtained. The electron spectra are shown in Fig.2(b) at the D_2's energy dependence $\alpha = 0.3,\ 1.0$. The smaller the value of α, the more modulated the electron spectrum with increasing energy. The observed data below 10GeV seem to be generally agreement with the curve of $\alpha = 1$.

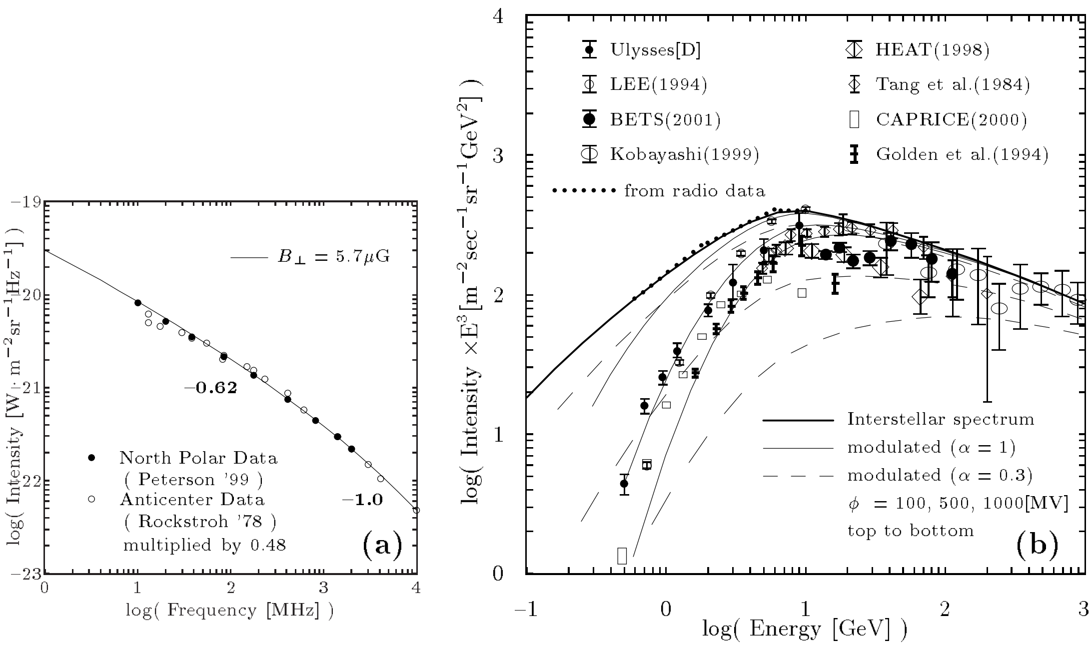

Fig. 2. (a)The radio data in the polar direction [*Peterson 1999*] and in the anticenter data [*Rockstroh 1978*] multiplied by 0.48 for normarization at 2GHz. The synchrotron spectrum (solid line) is estimated from LIS shown in (b) with $B_\perp = 5.7\mu$G. (b) LIS and modulated electron spectra compared with compiled measurements. The D_2's energy dependence $\alpha = 0.3,\ 1$ and the different values of ϕ in eq. (2).

4. Conclusions

Using the force-field approximation, we gave the relations between the modulation parameter Φ and the Climax NM count rate N_c. The Φ-N_c curve of 11GV protons has the slope of $-0.5 \sim -0.8$ and the Φs estimated from the electron measurements are separated by the solar polarity. According to Fig.1(a), nuclei lines estimated by Badhwar et al.[1] are between the A>0 and A<0 curves of electrons. If this is the case, it indicates that the magnitude of solar modulation changes between the positive and negative cosmic rays every solar polarity reversal. We have also shown the modulated electron spectra, which are so sensitive to α that pricise measurements below 100GeV will give some information on α.

References

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