Particle Acceleration by Oblique Shocks and Cosmic Ray Composition in the Knee Region

K. Kobayakawa[1], **Y. Sato**[2], **and T. Samura**[1]

[1] *Fukui University of Technology, Gakuen 3-6-1, Fukui, Fukui, 910-8505, Japan*

[2] *Graduate School of Science and Technology, Kobe University, Nada-ku, Kobe, 657-8501, Japan*

Abstract

The first order Fermi acceleration of cosmic ray particles is considered on the assumption that the shock fronts meet outer magnetic fields at definite but various angles to the shock normals. Then, the acceleration by oblique shocks is essential. It is shown that the behavior of the knee in the primary cosmic ray spectrum and the change of its chemical composition are strongly dependent on the maximum energy per particle which can be achieved with this acceleration mechanism. Our results fit closely with several recent experimental data.

1 Introduction

It is one of the most important clues to resolve the acceleration mechanism of cosmic ray particles in explaining the energy spectrum of primary cosmic rays. Above all, acceleration caused by an oblique shock around a supernova remnant is quite significant for the behavior at knee energies ($\sim 2 \times 10^{15}$ eV).

Our model is as follows. After a supernova explosion, a shock wave is formed around its remnant and expands almost spherically symmetrically. It is therefore assumed that the interstellar magnetic field meet the shock normal at random incident angles. Based on this assumption, we have calculated the energy spectrum and energy dependence of the chemical composition of primary cosmic rays. Our results can explain the knee behavior and fit closely with recent data of balloon and air shower experiments.

2 Methods

Suppose a shock whose front is moving at a non-relativistic speed U_1. The shock normal crosses magnetic field lines B_1 at an angle α_1 in the upstream rest frame. The energy of a cosmic ray particle is conserved during the interaction with the shock front if the amplitudes of magnetic field fluctuations are sufficiently small compared with the average field. Then, the characteristic acceleration time t_{acc} can be expressed by upstream parameters only (Ostrowski, 1988; Takahara, 1990),

$$t_{acc} = \frac{3r}{U_1^2(r-1)}\kappa_B x \left[\cos^2\alpha_1 + \frac{\sin^2\alpha_1}{x^2} + \frac{r(\cos^2\alpha_1 + \frac{r^2}{x^2}\sin^2\alpha_1)}{(\cos^2\alpha_1 + r^2\sin^2\alpha_1)^{\frac{3}{2}}}\right], \tag{1}$$

where κ_B is the Bohm diffusion coefficient and r denotes the compression ratio of the shock. The x is defined as the ratio of the diffusion coefficient of parallel to shock normal to κ_B and its value is of the order of inverse square of field fluctuations $(\frac{B}{\delta B})^2$. To derive the maximum energy per particle which can be achieved with this acceleration mechanism, we put the characteristic acceleration time equal to the lifetime of the shock $t_{sh} = R_{sh}/U_1$ in accordance with Lagage & Cesarsky (1983),

$$E_{max} = \frac{R_{sh}(r-1)}{rcx}U_1 eBZ \left[\cos^2\alpha_1 + \frac{\sin^2\alpha_1}{x^2} + \frac{r(\cos^2\alpha_1 + \frac{r^2}{x^2}\sin^2\alpha_1)}{(\cos^2\alpha_1 + r^2\sin^2\alpha_1)^{\frac{3}{2}}}\right]^{-1}. \tag{2}$$

Although there are also some other causes to restrict the acceleration such as energy losses of particles and leakage from the galaxy, they are negligible at such a high energy level. Substituting the various constants for corresponding typical values and defining $\eta \equiv \cos\alpha_1$, we express E_{max} as a function of η and x,

$$\begin{aligned} E_{max} &= 2.5 \times 10^{16}[\mathrm{eV}] \left(\frac{B}{30\mu\mathrm{G}}\right) \left(\frac{R_{sh}}{3\mathrm{pc}}\right) \left(\frac{U_1}{10^7\mathrm{m/s}}\right) \\ &\quad \frac{Z}{x}\frac{r-1}{r}\left[\eta^2 + \frac{1-\eta^2}{x^2} + \frac{r\{\eta^2 + \frac{r^2}{x^2}(1-\eta^2)\}}{\{\eta^2 + r^2(1-\eta^2)\}^{\frac{3}{2}}}\right]^{-1} . \end{aligned} \tag{3}$$

E_{max} in quasi-perpendicular shocks is two or three orders of magnitudes larger than in quasi-parallel shocks for each value of x. Here we choose the numerical value 2.5×10^{16} according to the recent papers. B is taken three (Bykov & Toptygin, 1997; Klepach et al, 1997) and 80/9 times following to Berezhko (1997) than ordinary values (for example Gaisser, 1990).

3 Results

Based on the result that angular dependence of the maximum energy is quite significant, we propose a simple model in which a supernova remnant shock expands almost spherically symmetrically and a uniform distribution of η is assumed. Here we neglect the possibility that magnetic field lines tend to be perpendicular to the shock front because of Rayleigh-Taylor instabilities (Biermann, 1993). Taking the condition that $U_1 \cos\alpha \leq c$ into account, we find $\eta \geq \frac{U_1}{c}$. The probability density of η is then

$$P_{rob} d\eta = \frac{d\eta}{1-\eta_{min}} \qquad \left(\eta_{min} = \frac{U_1}{c} = \frac{1}{30}\right), \tag{4}$$

where $(1-\eta_{min})^{-1}$ is a normalization factor. The region where $0 < \eta < \eta_{min}$ is not considered because this occupies only $\frac{1}{30}$ of total η. If there is an energy $E(\eta)$ which satisfies $E_0 \leq E(\eta) \leq E_{max}(\eta_{min})$, η is restricted within the region between η_{min} and 1. Thus, the energy flux at $E(\eta)$ should be multiplied by the factor $\frac{\eta-\eta_{min}}{1-\eta_{min}}$. The flux doesn't depend on η in the region where $E < E_0$. As for a strong shock, the spectral index -2 is independent of η and is assumed to be changed into -2.58 in consideration of "leaky box model". In summary, the energy differential flux can be expressed as:

$$\begin{aligned} \frac{dJ}{dE} &= CE^{-2.58} & (E < E_0) \\ &= CE^{-2.58}\frac{\eta-\eta_{min}}{1-\eta_{min}} & (E_0 \leq E \leq E_{max}(\eta_{min})) \\ &= 0 & (E_{max}(\eta_{min}) < E), \end{aligned} \tag{5}$$

where C is a constant. This η-dependent factor may cause the bent of the spectrum around the knee energy.

Although the value of x is considered to lie between 10 and 100, for simplicity we fix it at their geometrical mean, $x = 30$. Then, the cut of rigidity in parallel shock, $R_{cut} = 1.25 \times 10^{14}$ V and $E_{max}(\eta_{min})$ for Fe is 2.5×10^{18} eV. We show our total energy spectrum and its each component in Fig. 1 and compare the total spectrum with various experimental data (Amenomori, 1996). Our flux for each component is normalized to the experimental data at 10^{12} eV (Ichimura, 1993). Our theoretical curve (total) shows a good agreement with experimental data around knee energy. In the energies higher than 10^{17} eV, however, our model shows a slight discrepancy from experiments. This is a natural consequence on account of the rigidity cut of our model. This probably indicates contribution from other sources such as pulsar or AGN (Frank et al, 1992).

Next we comsider the energy dependence of chemical composition. We introduce the average value of the logarithm of mass number A as a good indicator of the composition,

$$<\ln A>\equiv \frac{\sum_i f_i(\ln A_i)}{\sum_i f_i},$$

where A and f are mass numbers and fluxes, respectively, and suffix i denotes the specy of each element. Using our results of f_i, $<\ln A>$ is shown in Fig. 2. Our theoretical curve is constant approximately with the initial value 1.45 up to 1.25×10^{14} eV and then rises with energy slowly. In our model, light elements such as proton and He are abundant in low energy regions and heavy elements like sub-Fe and Fe are dominant in high energy regions. Our curve is somewhat lower than many of experimental data (Kakimoto, 1995). Some experiments, however, suggest lower values of $<\ln A>$. In the experiment of Ohya group (Mitsui et al., 1995), $<\ln A>$ is $1.12^{+0.6}_{-0.28}$ from 2×10^{14} eV to 2×10^{15} eV and is 2.14 ± 0.37 from 2×10^{15} eV to 2×10^{16} eV. Some authors say that $<\ln A>$ decreases in energy regions larger than the knee (Kasahara et al, 1997 ; Boothby et al, 1997).

4 Conclusions and Discussion

Based on the assumption that outer magnetic fields cross the shock normal at random angles in the framework of the first Fermi acceleration, we have succeeded in reproducing the total energy spectrum. Especially, its knee behavior can be derived without requiring additional spectra in regions above the knee energy. Our model, however, will be limited to energies per particle less than $\sim 10^{17}$ eV. In energy higher than that, sources other than ordinary supernova remnants will be necessary, such as OB-associations (Bykov & Toptygin, 1997), pulsars, AGN and so on.

For the compositions $<\ln A>$, our curve seems to be lower than experimental data. When we take less R_{cut} in the present model, $<\ln A>$ rises from less energies and the knee energy becomes lower. The dependence of $<\ln A>$ on energies is experimentally not settled sharply.

Here we neglect the dependence of power indices on obliqueness (Naito & Takahara, 1995) and the quasi-perpendicular case where de-Hofmann-Teller frame cannot be used. These are problems remaining to be solved.

References

Amenomori, M. et al., 1996, ApJ 461, 408

Biermann, P. L., 1993, A&A 271, 649

Boothby, K. et al., 1997, ApJ 491, L35

Bykov, A. M. & Toptygin, I. N., Proc. 25th ICRC (Durabn, 1997) 4, 365

Costa, C. G. S. et al., 1996, Phys. Rev. D45, 5558

Berezhko, E. G., 1997, Astrop. Phys. 5, 367

Bernlö, K., 1988, Astrop. Phys. 8, 253

Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (Cambridge Astrophysics Series 21: Second Edition)

Gaisser, T. K., 1990, Cosmic Rays and Particle Physics (Cambridge University Press)

Ichimura, M., et al., 1993, Phys. Rev. 48, 1949

Kakimoto, F., 1995, private communication

Kasahara, S. M. et al., 1997, Phys. Rev. D55, 5282

Klepach, E. G. et al., Proc. 25th ICRC (Durban, 1997) 4, 501

Lagage, P. O., & Cesarski, K., 1983, ApJ 118, 223

Mitsui, K., et al., 1995, Astrop. Phys. 3, 125

Naito, T., & Takahara, F., 1995, Prog. Theor. Phys., 93, 287

Ostrowski, M., 1988, MNRAS 233, 257
Swordy, S. P., Proc. 25th. ICRC (Rome, 1995) 2, 697
Takahara, F., 1990, Prog. Theor. Phys., 83

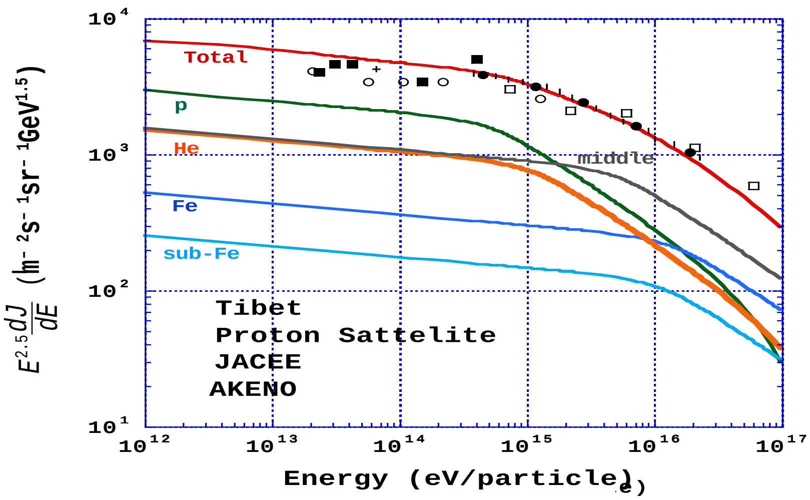

Figure 1: Energy spectrum of primary cosmic rays (Amenomori, 1996) compared with the present calculation. Our spectra of the five mass groups are also shown.

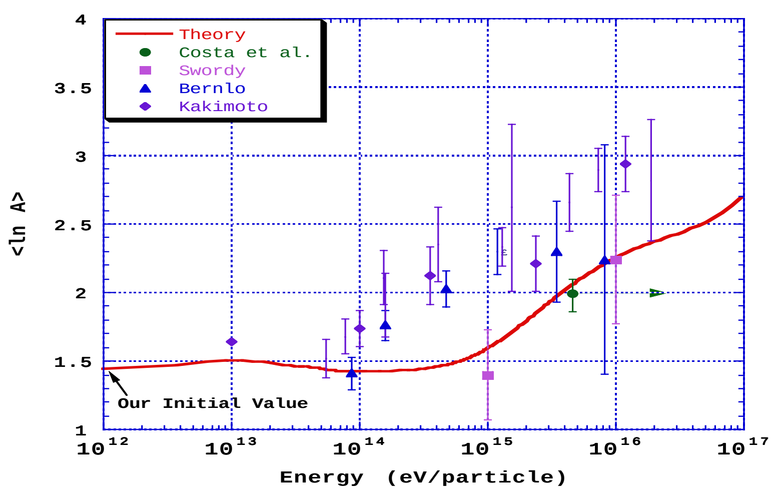

Figure 2: Comparison of our composition with experimental data (Costa 1996, Swordy 1995, Bernlö 1988, and Kakimoto's compilation, 1995).