IL NUOVO CIMENTO VOL. 20 C, N. 4 Luglio-Agosto 1997

Estimation of (Cl-Mn)/Fe flux ratio at relativistic energies using steady-state leaky-box model modified for reaccelerations

R. MAJUMDAR, B. BASU and D. P. BHATTACHARYYA
Department of Theoretical Physics, Indian Association for the Cultivation of Science
Jadavpur, Calcutta 700 032, India

(ricevuto il 27 Marzo 1996; approvato il 10 Ottobre 1996)

Summary. — The (Cl-Mn)/Fe flux ratio at the top of the atmosphere has been estimated from source composition. We have adopted the SSLB model modified for weak shocks to estimate the enhancement of (Cl-Mn)/Fe flux ratio due to reacceleration. The observed active detector results of Lezniak and Webber, Caldwell, Orth *et al.*, Engelmann *et al.*, and our passive detector results are fairly supported by the expected results from the SSLB model modified with reacceleration after Ferrando for energies $\leqslant 100$ GeV/n.

PACS 96.40 – Cosmic rays.
PACS 96.40.De – Composition, energy spectra, and interactions.

1. – Introduction

The steady-state leaky-box model (SSLB) by Cowsik *et al.* [1] for the propagation of cosmic rays assumes that once the particle leaves the source, its energy is not subjected to any energy gain during the propagation phase. However, the progress in the understanding of high-energy phenomena occurring in ISM has indicated the possibility of reacceleration of particles at the time of their propagation through ISM. Reacceleration of cosmic rays in the interstellar space has been studied to examine its effect on the secondary components of cosmic rays. It is expected that the shock waves from supernovae remnants propagating in the hot tenuous ISM could accelerate cosmic rays [2] during their passage in the ISM. The cosmic-ray power law spectrum in the range 1–10^5 GeV may be produced as a consequence of acceleration by supernova shocks [3]. The supernova remnants may occupy a substantial portion of the galactic volume. During the cosmic-ray residence time ions in the Galaxy suffer an additional acceleration by weaker shocks that are created by the supernova remnants (SNR). The reacceleration can change the cosmic-ray spectrum appreciably which reflects the energy dependence of the ratio of secondary to primary cosmic nuclei fluxes. Eichler [4] has shown that the B/C flux ratio strongly constrains an acceptable amount of reacceleration. Earlier Blanford and Ostriker [5] used a diffuse shock acceleration mechanism to explore the origin and subsequent propagation of cosmic rays in the

Galaxy. The blast waves from different supernovae start overlapping in such large ISM volumes. As a matter of fact, cosmic rays produced in SNR are reaccelerated by shock strengths from other remnants too. The supernova remnants fill a large fraction of the hot tenuous phase of ISM which can reaccelerate ambient cosmic rays. The strong shocks are not responsible for reacceleration which shows the steep nature of secondary nuclei spectra. The frequent encounter of cosmic rays with the weaker shocks causes a slow increase of the cosmic-ray energies. This may lead to acceleration and one needs to examine its consequences on all cosmic-ray components. Since higher-energy cosmic rays escape more freely from the Galaxy than the low-energy ones, the modification introduced by reacceleration would also be energy dependent. Such an effect would be noticeable for light elements. The concept of reacceleration can be adopted in the steady-state leaky-box model [1] to investigate the shape of the cosmic-ray spectra and to estimate the mass composition. Wandel *et al.* [6] have developed a model where the reacceleration of the primary cosmic rays has been taken into account due to its self-consistency. Recently, Wandel [7] has improved that model by considering significant reacceleration by strong shocks available from young SNR that lead to flattening on the secondary to primary ratio at high energies (> 10 GeV). The path length distribution is a crucial astrophysical parameter used in the propagation calculation since it links to the condition and mechanism of cosmic-ray confinement. Heinbach and Simon [8] have calculated sub Fe/Fe flux ratio that agrees with the experimental results under 30% reacceleration and the energy enhancement occured within $3.1\ \mathrm{g\,cm^{-2}}$, along with the pathlength expression of the form $\lambda_{\mathrm{esc}}(E) \sim 7\ (R/2.2)^{-0.4}$ for $R > 2.2$ GV. The energy dependence of λ_{esc} above a few GeV/n becomes weaker according to Simon *et al.* [9]. Letaw *et al.* [10] have studied the behaviour of sub Fe/Fe ratios at high energies under distributed reacceleration in the SSLB model. They used energy-indpendent cross-sections neglecting ionization losses and solar modulation. These results differ from each other for $E < 5$ GeV/n. Ferrando *et al.* [11] pointed out that the amount of energy gain by reacceleration $\langle \mathrm{d}E/\mathrm{d}x \rangle^{\mathrm{reac}} = \eta\, E_{\mathrm{tot}} R^{-\alpha}$ for escape length $\Lambda_{\mathrm{e}}(R) \sim R^{-\alpha}$.

In the present work we have estimated (Cl-Mn)/Fe flux ratio at ISM from the assumed source spectrum by adopting the SSLB model developed by Garcia-Munoz *et al.* [12]. Our calculated (Cl-Mn)/Fe flux ratio from the SSLB model was duly corrected by considering the amount of enhancement of the intensity due to reacceleration following the term of Ferrando *et al.* [11]. The derived (Cl-Mn)/Fe flux ratios expected from SSLB and that modified for reacceleration at ISM have been compared with active detector results of Lezniak and Webber [13], Caldwell [14], Orth *et al.* [15], Engelmann *et al.* [16] along with our plastic emulsion passive detector result.

2. – Nuclear physics and formulations

The steady-state leaky-box model (SSLB) developed by Cowsik *et al.* [1] which was later reproposed for general application on cosmic-ray propagation by Garcia-Munoz *et al.* [12] relates the source spectrum Q_i with the interstellar spectrum by the form

$$Q_i = N_i + \frac{N_i}{\lambda_i} + \sum_{j>i} \frac{N_0}{A_{\mathrm{T}}} \sigma_{ij} N_j\,, \tag{1}$$

where λ_i is the interacting length of i-species, σ_{ij} is the spallation cross-section for species $j(>i)$ to fragment into species i taken from Tsao *et al.* [17] and A_T is the target mass.

The total charge-changing cross-section σ_i for the interaction of the projectile of mass number A_P with the target of mass number A_T can be calculated from the formulation of Nilsen *et al.* [18] and follows the relation

$$\sigma_i = 10\Pi r_0^2[A_T^{1/3} + A_P^{1/3} - \Delta R]^2 \tag{2}$$

and the corresponding overlap parameter ΔR follows:

$$\Delta R = [\delta - \varepsilon A_T - b' A_P^{1/3} A_T^{1/3}], \tag{3}$$

where δ, ε and b' are constants and can be obtained from the accelerator experiments.

We have considered the energy dependence confinement lifetime $\tau_{esc}(E)$ in a similar manner as used earlier by Letaw *et al.* [10] which follows the power law

$$\tau_{esc}(E) = 1.27189 \cdot 10^7 E^{-0.437991} \qquad \text{for } E > 2 \text{ GeV/n}. \tag{4}$$

The energy of Fe nuclei $E(0)$ at the observed atmospheric depth and that at the top of the atmosphere $E(x)$ can be related by taking into account the energy loss due to inelastic interactions considering the reaction $\mathrm{Fe} + A \rightarrow \mathrm{Fe} + X$, where A stands for the mass number of air medium after Hayakawa [19], which follows the form

$$E(x) = E(0) \exp[Kx/\lambda_{Fe}], \tag{5}$$

where K is the inelasticity of Fe + A (air) interactions, λ_{Fe} is the interaction mean free path of Fe in air, x is the distance traversed by cosmic-ray nuclei from the depth of the observation to ISM.

The theoretical curve for secondary to primary flux ratio after Garcia-Munoz *et al.* [12] can be estimated using the relation

$$\frac{S}{P} = \frac{\sigma_{ij}}{A_T/\lambda_{esc} N_0 + \sigma_i}, \tag{6}$$

where N_0 is the Avogadro number and the partial and total cross-sections, *viz* σ_{ij}, σ_i, are the same as in (1).

The escape pathlength Λ_{esc} is related to the rigidity R of the Fe nuclei by a power law for above a certain critical rigidity R_c:

$$\Lambda_{esc} = \Lambda_a (R_c/R)^\alpha, \qquad \text{for } R > 4 \text{ GV}, \tag{7}$$

where the characteristic length Λ_a and the exponent α are chosen parameters.

The enhancement of the elemental intensity at the source due to reacceleration can be estimated using the relation given by Ferrando [11],

$$R_i = \left[\frac{\mathrm{d}}{\mathrm{d}E} \frac{\mathrm{d}E^{\text{reac}}}{\mathrm{d}x}\right] N_i. \tag{8}$$

The systematic average energy gain is described by the strength η as

$$\frac{\mathrm{d}E^{\mathrm{reac}}}{\mathrm{d}x} = \eta E_{\mathrm{total}} R^{-\alpha}\,. \tag{9}$$

3. – Results and discussion

We have used relations (1) to (4) for the derivation of elemental abundance at the top of the atmosphere from the assumed elemental (Ne-Ni) source composition of cosmic-ray nuclei. In eq. (2) we consider that the entire ISM is filled with 100% hydrogen which is treated as stellar target of effective atomic weight $A_{\mathrm{T}} = 0.089$ and the projectile mass A_B varied from 20.17 to 58.69 and $\Delta R = 0.92$ for $\delta = 1.0074$, $\varepsilon = 0.013$, $b' = 0.048$. From relation (4) the confinement lifetime at energy $E = 8.2$ GeV/n is estimated and found to be $5 \cdot 10^6$ year for $\beta = v/c = 0.9875$. The average interstellar density is taken to be 0.2 atoms/cm^3. Putting these parametric values in eq. (1), the relative abundance at the top of the atmosphere is estimated and displayed in table I.

The energy of the VH components in Fuji ET-7B nuclear emulsion is obtained from the opening angle method in a recent investigation by Bhattacharyya *et al.* [20] and found to be $E(0) = 5.0$ GeV/n. Using relation (5) and considering $K = 0.66$ for air, $x = 9.8\ \mathrm{g\,cm^{-2}}$, λ_{Fe} in air $= 13.2\ \mathrm{g\,cm^{-2}}$, the energy $E(0)$ is extrapolated to the incident Fe nuclei energy at the top of the the atmosphere as $E(x) = 8.2$ GeV/n.

Using relation (6) the theoretical curve of (Cl-Mn)/Fe flux has been estimated from SSLB model and is plotted in fig. 1. In this framework the escape length is taken as an energy-dependent parameter and with the characteristic length $\Lambda_a = 2.85$ and $\alpha = 0.3$ as chosen parameters, respectively.

The theoretical curve of (Cl-Mn)/Fe flux ratio after the SSLB model modified for reacceleration is also displayed in fig. 1 as a function of energy considering the enhancement factor from eq. (8) as $\eta = 0.6$ and $E_{\mathrm{total}} = 9.138$ GeV/n for $E_{\mathrm{top}} = 8.2$ GeV/n and rest mass $= 0.938$ GeV/n.

TABLE I. – *This table shows the abundance at the top of the atmosphere obtained from source abundances relative to* Fe *nuclei.*

Element	Source composition ratio relative to Fe nuclei		Composition at the top of the atmosphere relative to Fe nuclei	
	present work	Juliusson *et al.* [21]	present work	Engelmann *et al.* [16]
Cl	0.013	− 0.013	0.056	0.052
Ar	0.075	0.053	0.126	0.093
K	0.016	− 0.009	0.058	0.070
Ca	0.098	0.089	0.151	0.172
Sc	0.001	0.000	0.044	0.031
Ti	0.022	− 0.031	0.073	0.096
V	0.024	0.040	0.061	0.052
Cr	0.055	− 0.022	0.107	0.113
Mn	− 0.016	0.022	0.057	0.083
Fe	1.000	1.000	1.000	1.000

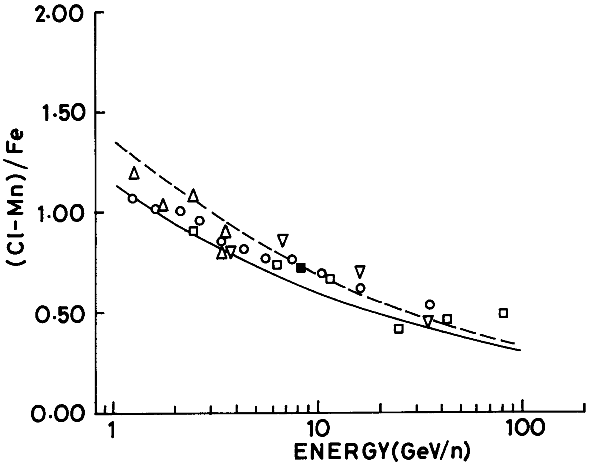

Fig. 1. – Shows the (Cl-Mn)/Fe flux ratio derived from the SSLB model and modified SSLB model for reacceleration phenomena along with the experimental results. Full and broken curves are the derived results expected from the SSLB model [12] with reacceleration and without reacceleration terms [11]. Experimental data: △ ref. [13], □ ref. [14], ▽ ref. [15], ○ ref. [16], ■ present work. Theoretical curve: —— SSLB model without reacceleration, – – – SSLB model modified with reacceleration.

It is evident from the plot that our observed passive detector data along with other active detector data of Lezniak and Webber, Caldwell, Orth *et al.*, and Engelmann *et al.* are supported by the derived result when corrected for reacceleration phenomena.

4. – Conclusion

When considering the experimental results on (Cl-Mn)/Fe flux ratios available from active and passive detector balloon and satellite-borne experiments compared with the derived result expected from the SSLB model modified for reacceleration, a fair agreement is found for energy above 3 GeV/n. The enhancement of cosmic-ray intensity due to reacceleration is fairly supported by the present survey.

* * *

One of us (BB) is thankful to CSIR for the award of a Research Associateship.

REFERENCES

[1] COWSIK R., PAL Y., TANDON S. N. and VERMA R. P., *Phys. Rev. D*, **158** (1967) 1238.
[2] AXFORD W. I., *Proc. XVII ICRC, Paris*, **2** (1981) 327.
[3] COWSIK R., *Astron. Astrophys.*, **155** (1986) 144.
[4] EICHLER D., *Astrophys. J.*, **237** (1980) 809.
[5] BLANFORD R. D. and OSTRIKER J. P., *Astrophys. J.*, **237** (1980) 791.
[6] WANDEL A., EICHLER D. S., LETAW J. R., SILBERBERG R. and TSAO C. H., *Astrophys. J.*, **317** (1987) 277.

[7] WANDEL A., *Proc. XXI ICRC, Adelaide*, **3** (1990) 357.

[8] HEINBACH U. and SIMON M., *Proc. XXI ICRC, Adelaide*, **3** (1990) 361.

[9] SIMON M., HEINRICH W. and MATHIS K. D., *Astrophys. J.*, **300** (1986) 32.

[10] LETAW J. R., SILBERBERG R., TSAO C. H., EICHLER D., SHAPIRO M. M. and WANDEL A., *Proc. XX ICRC, Moscow*, **2** (1987) 222.

[11] FERRANDO P., *Proc. XXIII ICRC, Calgary*, **5** (1993) 279.

[12] GARCIA-MUNOZ M., SIMPSON J. A., GUZIK T. G., WEFEL J. P. and MARGOLIS S. H., *Astrophys. J. Suppl.*, **64** (1987) 269.

[13] LEZNIAK J. A. and WEBBER W. R., *Astrophys. J.*, **223** (1979) 676.

[14] CALDWELL J. H., *Astrophys. J.*, **218** (1977) 269.

[15] ORTH C. D., BUFFINGTON A., SMOOT G. F. and MAST T. S., *Astrophys. J.*, **226** (1978) 1147.

[16] ENGELMANN J. J., FERRANDO P., SOUTOUL A., GORET P., JULIUSSON E., KOCH-MIRAMOND L., LUND N., MASSE P., PETERS B., PETROU N. and RASMUSSEN I. I., *Astron. Astrophys.*, **233** (1990) 96.

[17] TSAO C. H., SILBERBERG R., BARGHOUTY A. F., SHIVER L. and KANAI T., *Phys. Rev. C*, **47** (1993) 1257.

[18] NILSEN B. S., WADDINGTON C. J., CUMMINGS J. R., GARRARD T. L. and KLARMANN J., *Phys. Rev. C*, **52** (1995) 3277.

[19] HAYAKAWA S., *Cosmic Ray Physics* (John Wiley & Sons Inc., New York) 1969, p. 485.

[20] BHATTACHARYYA D. P., MAJUMDAR R., BASU B., PAL P. and FUJII M., *Nuovo Cimento C*, **18** (1995) 161.

[21] JULIUSSON E., CESARSKY C. J., MENGUZZI M., CASSÈ M. *et al.*, *Proc. XV ICRC, Munchen*, **2** (1975) 653.