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Observations of Enhanced Sub-Iron (Sc–Cr) to Iron Abundance Ratios in the Low Energy Galactic Cosmic Rays in Spacelab-3 and their Implications

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Abstract. The Anuradha cosmic ray experiment in Spacelab-3, flown in the orbit at 350 km with an inclination of 57° for about six days, was used to measure the low energy galactic cosmic ray (GCR) heavy ions using a specially designed CR-39 detector module incorporating the arrival time information of the particles. The abundances of sub-iron (Sc–Cr) and iron particles in the low energy interval of 30–300 MeV/N were determined from the measurements made in four different depths of the CR-39 detector module of 150 layers. From these studies we obtained sub-iron (Sc–Cr) to iron abundance ratios of 0·8 to 1·2 in 30–300 MeV/N energy range. It is found that these ratios are enhanced by a factor of two as compared to interplanetary ratios of about 0·5. It is shown that the enhancement of the ratio inside the earth's magnetosphere is probably due to the degree of ionization of low energy Sc to Cr and Fe ions in the galactic cosmic rays and to the rigidity filtering effects of the geomagnetic field. Further studies are needed to understand fully the phenomena and their implications.

Key words: Cosmic ray abundances—subiron and iron nuclei—space lab-3—Anuradha experiment

1. Introduction

For over two decades, there have been studies on the abundance ratios of sub-iron (Sc–Cr) to iron nuclei in the galactic cosmic rays, as it is well known that the sub-Fe nuclei are produced by the fragmentation of iron nuclei in collision with interstellar matter and hence the ratios of (Sc–Cr)/Fe are sensitive indicators of the amount of matter traversed by the galactic cosmic rays in the interstellar medium (see e.g. Shapiro & Silberberg 1970). These abundance ratios have also been used to determine the shape of the path length distributions in interstellar medium. The results obtained in the energy range > 500 MeV/N showed that path lengths and their distributions, which give best fit to the secondary to primary ratios of boron to carbon, do not exactly fit the (Sc–Cr)/Fe ratios. Hence, one invokes the hypothesis of truncation of path length distributions at short path lengths, that implies more than one confinement volume for cosmic ray heavy ions. These problems have been discussed by several authors (e.g. Garcia-Munoz *et al*. 1984; Soutoul *et al*. 1985; Guzik & Wefel 1984 and Ferrando *et al*. 1991).

When the measurement of the sub-iron to iron abundance ratio was extended to lower energies ($E \leqslant 300$ MeV/N) in the Skylab cosmic ray experiment, it was found for the first time that the abundance ratio at low energy of 35–250 MeV/N was significantly higher than that at high energies (Biswas *et al.* 1975; and Durgaprasad & Biswas 1988). It was, therefore, necessary to conduct such an experiment with higher statistical accuracy. The Anuradha cosmic ray experiment in the Spacelab-3 Mission was specially suitable for such studies. Initial results on the (Sc–Cr)/Fe abundance ratio measured in the lowest energy range in the Spacelab-3 also showed enhanced values and these were reported in international conferences (Biswas *et al.* 1987, 1989; Durgaprasad et *al.* 1990a, b). Since then additional measurements were carried out and the sub-iron (Sc–Cr) to iron abundance ratios were measured at four different depths of the detector. From these, the abundance ratios were obtained in four energy intervals, from 30 to 300 MeV/N. These final results and interpretations are presented in this paper.

The experiment conducted in the Soyuz-6 mission by USSR group (Gagarin *et al.* 1990) also reported enhanced values of the ratios at low energies, confirming the data from the Skylab and Spacelab-3 experiments. Thus it is established that inside the earth's magnetosphere, the sub-iron (Sc–Cr) to iron abundance ratio is about 1.0 in the 30–300 MeV/N energy region, which is about a factor of two enhanced as compared to the interplanetary values measured in IMP-8, ISEE-3 and Voyager-2 spacecrafts (Garcia-Munoz *et al.* 1987; Leske & Widenbeck 1990; Ferrando *et al.* 1991). The reasons for the enhancements were not understood earlier and this has been a puzzling problem.

In this paper, after presenting the experimental procedure and results, we discuss the implication of the results and show that the enhancements of the ratios inside the magnetosphere can be understood in terms of the new findings in the Spacelab-3 cosmic ray experiment. It is found by Biswas *et al.* 1990, Singh *et al.* 1991 and Dutta *et al.* 1993, that about 25% of low energy (30–130 MeV/N) sub-iron (Sc–Cr) and Fe particles in galactic cosmic rays are in partially ionized states. These observations together with the rigidity filtering process of the earth's magnetic field are used to explain the enhancement effects, as discussed in this work.

2. Experimental procedure and results

The Anuradha cosmic ray experiment in Spacelab-3 of NASA was flown in space at an altitude of 350 km in a circular orbit at an inclination of 57° to the equator in a six-day mission during April 29–May 6, 1985. The detector module consisted of (a) a top fixed stack of a single sheet of CR-39 of diameter about 40 cm and of thickness 0.33 mm and (b) a movable stack of 149 CR-39 sheets each of nominal thickness of about 0.25 mm. The two stacks were separated from each other by a fixed gap of 0.5 mm. The bottom stack was rotated with respect to the fixed top stack at a slow uniform rate in steps of 40 sec of arc once in 10 sec. By identifying the track segments in the upper fixed and the lower movable stack and measuring their displacements, the arrival time of the cosmic ray heavy ions were determined. This information, together with other measured properties of the particles, was used to determine the ionization states of the anomalous and low energy GCR heavy ions. The details of the instrument, experimental method and procedure for analysis have been reported earlier (Biswas *et al.* 1986; Biswas *et al.* 1990; Singh 1990; Singh *et al.* 1991; Dutta *et al.* 1993). Here we briefly present the relevant aspects of the procedure for the analysis of subiron and iron abundance ratios and the results obtained.

The shielding above the detector consisted of 25 mg cm $^{-2}$ of aluminium alloy and 0.5 mil of aluminised mylar (Kapton) so that GCR iron ions, of energy 25 MeV/N and above, could be detected. The topmost detector sheet was numbered as 1–0 and subsequent sheets as 1–1 to 1–150. For sub-iron and iron abundances ratios, the scanning and measurements of GCR heavy ions were carried out in four different depths of the detector. A pair of plates were scanned at a time. These were plates of numbers (1) 1–0 and 1–1, (2) 1–2 and 1–3, (3) 1–14 and 1–15, (4) 2–50 and 2–51. Each pair of CR-39 plates were scanned for double cones in each plate so that, in general, four cones of each of the particles were seen in the pair of plates. The selected cones are followed through successive plates till the particles were brought to rest in the stack. Using cone length vs residual range, the identification of the atomic number of the particles were made. With the track selection procedure used, cosmic ray particles of $Z > 10$ were identified, and the particles of $Z > 20$ were used in the analysis. It may be noted, that in our etching conditions, maximum etched length was about 0.3 mm for Mg ions which increased rapidly to about 3 mm for Fe particles. Hence the Fe-group particles could be followed in as many as about 15 plates and a large number of independent measurements of nuclear charge could be made for the GCR particles of $Z = 21$ to 28 in the detector and their identity could be well established. The detailed analysis of the charge resolution of the particles obtained in the experiment, was made by Yadav & Singh (1990), who showed that the standard deviation of the charge determination for a single cone measurement obtained by the deconvolution method is given by the equation $\sigma(z) = 0.285 + 0.03Z$, where Z is the atomic number and $\sigma(z)$ the standard deviation of the charge value. For Fe nuclei $\sigma(z) \approx 1$ charge unit for a single cone observation. On the average about nine cones were measured for Fe ions in this experiment. Hence the charge resolution is obtained as 0.3 charge units for Fe-ions. Thus the atomic number of the particles of Sc to Ni could be unambiguously determined. Fig. 1 shows the observed histogram of the mean fractional charges of Ti to Ni events in this study. It is pointed out that the response function in CR-39 of cosmic ray heavy ions increases rapidly with the atomic number Z and hence the respective response functions are to be used to determine their relative abundances.

In Table 1, we show the results of the abundance ratios of (Sc–Cr)/Fe from the present work, carried out at four different depths in the detector module. The energies of particles given in Table 1 refer to those at the top of the detector module. When measured fluxes of sub-iron (Sc–Cr) and of Fe are in slightly different energy intervals, corrections for the relative response functions are made to obtain the corrected abundance ratio. For measurements made in the lower depths of stacks in plates 2–50 and 2–51, the measured fluxes and (Sc–Cr)/Fe ratios are corrected for loss of particles due to nuclear interactions in the stack and also for the contribution to Sc–Cr fluxes by the fragmentation of Fe nuclei in the stack. For this purpose diffusion

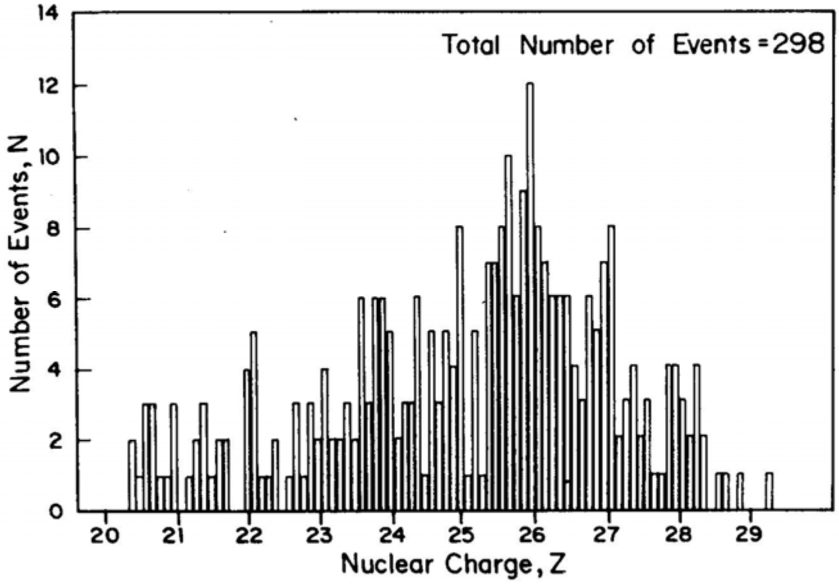

Figure 1. Observed histogram of sub-Fe and Fe ions.

Table 1. Sub-iron (Sc–Cr) to Fe abundance ratios in Spacelab-3.

Scan plates and area scanned	Event type and exposure time (hrs)	No. of events measured and used[a]	Energy interval MeV/N	Mean energy MeV/N	Measured (Sc–Cr)/Fe ratio	Extrapolated (Sc–Cr)/Fe ratio
(1–0)(1–1)	T.A.E.[b]	70				
400 cm^2	64	44	22–80	51	1.02 ± 0.30	1.02 ± 0.30
(1–0)(1–1)	S.S.E.[c]	52				
400 cm^2	72	46	30–120	75	0.59 ± 0.18	0.59 ± 0.18
(1–2)(1–3)	T.T.E.[d]	97				
	120	50	54–80	67	1.17 ± 0.28	1.17 ± 0.28
(1–14)(1–15)	T.T.E.	23				
	120	21	90–170	130	1.18 ± 0.52	1.15 ± 0.51
(2–50)(2–51)	T.T.E.	70				
	120	39	190–280	235	1.05 ± 0.33	0.97 ± 0.31

[a] No. of events 'used' is given by the lower number in the column and refers to those in selected overlapping energy intervals.
[b] Time annotated events.
[c] Stationary state events.
[d] Total time events.

equation with partial fragmentation cross sections are used.As depth in stack is small and amounts to only about 2.5 g cm^{-2},the correction is small and amounts to only ~10%.

The results obtained on (Sc–Cr)/Fe rations in the four energy intervals are shown in Fig. 2 together with those of other investigators measured in spacecrafts inside the

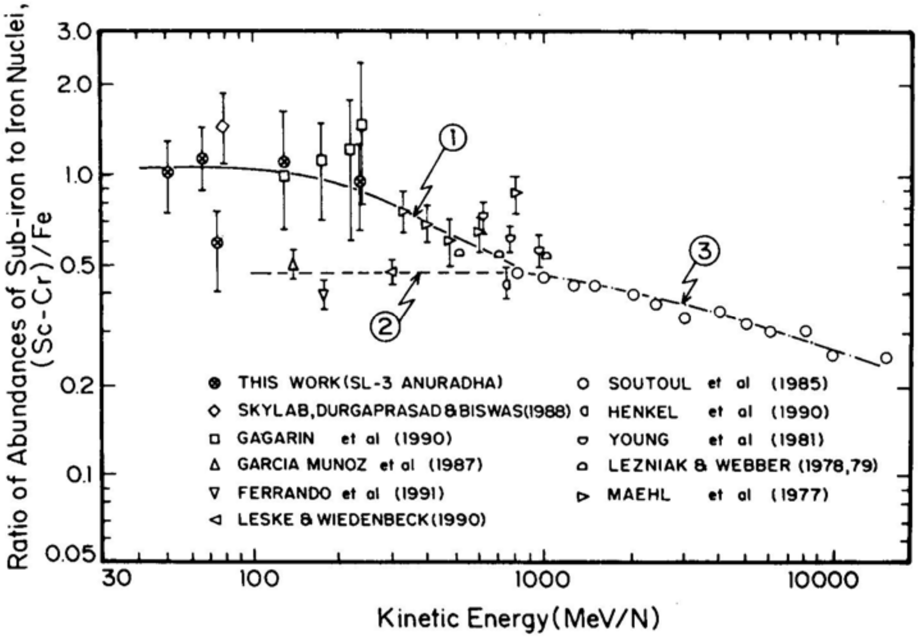

Figure 2. The ratio of abundances of (Sc–Cr) to Fe ions vs kinetic energy in 30 MeV/N to ~ 10 GeV/N. The eyefit line denoted by 1 represents approximate curve for the ratio measured inside the magnetosphere in Skylab,Spacelab-3 and Soyuz-6,whereas the eyefit line 2 shows the value of the ratio measured in the interplanetary space. The line 3 shows the variation of the ratio in the high energy region in 1–l0G eV/N measured in HEAO-3 spacecraft.

magnetosphere and outside of it. It is seen that the present results of Spacelab-3 are in good agreement with those of Skylab (Durgaprasad & Biswas 1988) and Soyuz-6 (Gagarin *et al.* 1990). An eye fit line drawn through these data is marked as 1. The HEAO-3 results of $E \sim$ 1–10 GeV/N are shown in this figure. In the same figure, it is seen that the interplanetary measurements of the ratio in IMP-8 (Garcia-Munoz *et al.* 1987), ISEE-3 (Leske & Widenbeck 1990) and Voyager-2 (Ferrando *et al.* 1990) are in good agreement with one another and these can be represented by a flat dashed line marked 2 which joins smoothly with the high energy HEAO-3 data marked as 3. It is seen that the ratios, measured at low energies (30–300 MeV/N) inside the magnetosphere are enhanced by a factor of about two, as compared to the interplanetary value of ~ 0.5.

3. Discussions

3.1 *Enhanced Abundance Ratios and Solar Modulation*

In this experiment the charge resolution is adequate to identify individual charges, as noted earlier. The energy determinations are made from the range measurements of stopping particles and hence these are accurately known. Hence the enhanced (Sc–Cr)/Fe ratios in the Spacelab-3 experiment can not be due to uncertainties of nuclear charge and energy determinations. Although individual data points have fairly large statistical errors, all the low energy measurements of the ratios inside the magnetosphere, taken together, clearly establish that the abundance ratios inside the magnetosphere are enhanced by a factor of about two as compared to the interplanetary ratio.

The sub-iron to iron ratios measured inside the magnetosphere are only weakly dependent on solar modulation. The Skylab measurements were made in 1973–74 which were close to climax neutron monitor maxima of 1976 and the Spacelab-3 Anuradha experiment was conducted in 1985 at low level of solar activity, about two years prior to neutron monitor maximum of 1987. The Soyuz data refer to 1978–79, when neutron monitor rate was close to that of Spacelab-3 of 1985. Hence the solar modulation effects should be small and somewhat similar for the three results. Also, these effects can be neglected in the present data, where statistical errors are fairly large

It is seen in Fig. 2, that the eye fit line through the low energy (30–300 MeV/N) data smoothly joins the HEAO-3 data at high energies (1 to 15 GeV/N). In the intermediate energy range of 300–500 MeV/N, the balloon data of the ratios are consistent with the line (1) and the data of 500–1000 MeV/N are consistent with the lines (1) and (2) as these are close to each other. In discussing the enhanced (Sc–Cr)/Fe ratios at low energy observed in Spacelab-3, Skylab and Soyuz-6, Wefel (1991) has questioned whether some of these sub-iron and iron particles could be due to the following process. An iron ion just above cut-off energy, travels to the mirror point in the upper atmosphere, where it loses energy and undergoes fragmentation and electron capture process, and thus enters the detector as a partially ionized particle. This process is not possible for two important reasons. Firsly, the amount of material traversed by an iron particle in the upper atmosphere is typically $\leqslant 0.1$ g cm^{-2}, whereas interaction length in air is about 10 g cm^{-2}. Hence fragmentation in upper atmosphere is not possible. Secondly, the sub-iron and iron ions measured by us are mostly in 50–100 MeV/N. At these energies, it is impossible for these particles to capture electrons, as the electron stripping cross section greatly exceeds the capture cross section. Hence the above suggestion can be completely ruled out. The electron capture near mirror point may be possible for Fe particles in the range of energy of 1–10 MeV/N, which are not considered in any of the present space experiments.

3.2 *Flux of Low Energy Fe-Nuclei and their Ionization States*

We discuss here the flux of iron nuclei and their ionization states which can be deduced from the measured data. It is now established (Biswas *et al.* 1988; Adams *et al.* 1991) that the fluxes and energy spectra of low energy GCR nuclei, measured both inside and outside the magnetosphere at the same time, together with the geomagnetic transmission factors, could be used to determine their mean ionization states. Here, we first compute the orbit average flux of Fe-nuclei in the 22–80 MeV/N interval for the time annotated events (as given in Table 1). The sample is selected, because these time-annotated Fe events were also used to determine the ionization states of individual ions by the trajectory computation method (Biswas *et al.* 1990; Singh *et al.* 1991; Dutta *et al.* 1993), and the results from both the methods could be compared. The orbit average flux for the 64 hr exposure was obtained as 2.47 ± 0.64 p/(M^2 Sr Sec MeV/N) for Fe-ions of 22–80 MeV/N. We derived the interplanetary Fe flux in the following

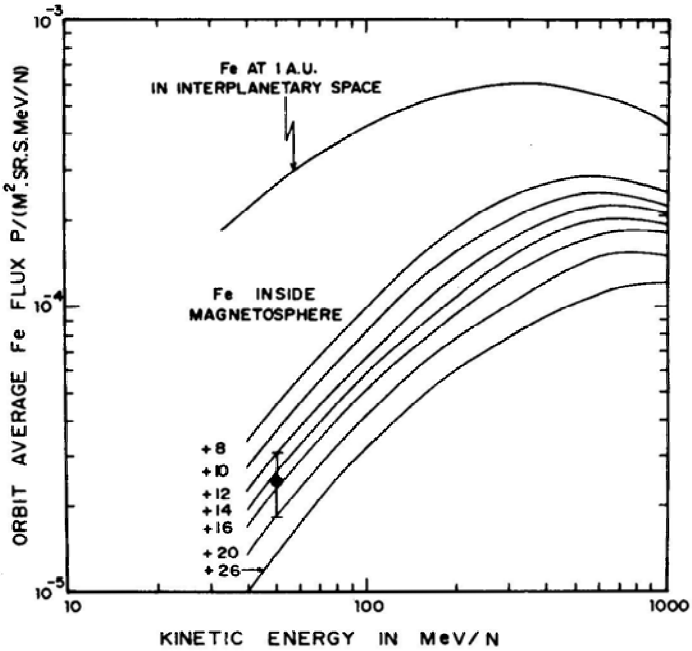

Figure 3. Fe-flux vs 1 AU outside the magnetosphere is shown in the uppermost curve, and the calculated orbit average Fe fluxes inside the magnetosphere are shown by the lower set of curves for assumed mean ionization states of Fe^{+8} to Fe^{+26}. The measured orbit average flux in SL-3 at 50 MeV/N is shown which indicates that the ionization state of these Fe particles is +15.

manner. We used the GCR oxygen flux measured in 45–300 MeV/N by Dutta (1991) in Spacelab-3 within the magnetosphere and as these GCR particles were fully stripped nuclei, their interplanetary flux at 1 AU could be determined. This determined flux agrees well with the demodulated spectrum of oxygen at 1 AU in 1985 and with the ISEE-3 data. Next we used the well known abundance ratio of Fe/O in GCR as 0.129 (Biswas & Durgaprasad 1980), to derive the Fe-energy spectrum at 1 AU in 1985, which is shown in Fig. 3. Then using geomagnetic transmission factors for Spacelab-3 orbit as given by Biswas *et al.* (1988), we calculate the expected orbit average fluxes of Fe-ions for different ionization states (Z^*) of + 8 to + 26. Thus from the measured orbit-averaged flux at 45 MeV/N, the mean ionization state of Fe-ions of 22–80 MeV/N is determined as $Z^* = 15$, as shown in Fig. 3. The measurements of the ionization states of the individual particles of the same sample of events by trajectory computation method was done by Biswas *et al.* (1990) and Dutta *et al.* (1993) and the upper limit of mean Z^* is obtained as + 20. Both these results are in agreement with each other.

3.3 *Ionizations States and the Abundance Ratios*

We now discuss and compute the enhancement of the abundance ratios by the rigidity filtering effect of the geomagnetic field. The partially ionized particles of Fe-group

Table 2. Calculated and measured ratios of (Sc-Cr)/Fe.

Ion	Mean degree of ionization Z^*/Z	Average A/Z^*	Average momentum/N Pc GeV	(A/Z^*) Pc = cut-off rigidity GV	Effective exposure factor	Calc. enhancement factor	Measured enhancement factor
Sc–Cr	0.71	3.1	0.37	1.14	> 0.091	> 1.2	2.2
Fe	0.80	2.7	0.37	0.99	0.079	1	1

will have higher magnetic rigidities and hence these will have higher exposure factors. The detailed computation of the effective exposure factors as a function of threshold rigidity for the Spacelab-3 Anuradha exposure is given by Biswas *et al.* 1988. We use these to calculate the effective exposure factors for sub-iron (Sc–Cr) and Fe ions. From the measurements of ionization states of cosmic ray ions in Spacelab-3 (Biswas *et al.* 1990; Singh *et al.* 1991; Dutta *et al.* 1993), we calculate the relevant parameters as shown in Table 2. It is seen that mean Z^*/Z of (Sc–Cr) is 0.71 as compared to 0.80 of Fe. These are based on 16 events of Sc to Cr and 22 events of Fe. This is indicative of the trend and further studies are needed to confirm this. In column 5 we show the mean values of $(A/Z^*) \times$ pc which is equal to rigidity. It is seen that effective cut-off rigidity for Sc–Cr is 1.14 which is about 14% higher than 1.0 of Fe. The effective exposure factors 0.091 and 0.079 are then obtained using the computation of effective exposure factor vs threshold rigidity (as given in figure 4 of Biswas *et al.* 1988). The calculated enhancement factor is then determined as (0.091/0.079) = 1.2. As Z^* is the upper limit, exposure factor can be larger; hence calculated enhancement factor may be > 1.2. This can be compared with the measured enhancement of 2.2.

3.4 *Ionization States and Interstellar Propagation of GCR Particles*

In order to understand the enhancements of the low energy (Sc–Cr)/Fe abundance ratios, we suggest the following scenario which is consistent with the standard model of cosmic ray origin and propagation. GCR heavy ions such as Fe originate from some galactic sources, e.g. SN, SNR, etc. and after being mixed with the ions of interstellar medium (ISM), they are injected with some initial acceleration into the ISM through which they propagate. In the GCR propagation in the galaxy, the following characteristic processes may occur:

(a) Interactions of GCR iron ions can take place with matter in ISM and could undergo fragmentation to sub-iron particles, e.g. Sc, V, Ti, Cr and Mn. Thus the well measured parameters of sub-iron to iron abundance ratios, together with the well-determined interaction and fragmentation cross sections, are used to determine the amount of material traversed by GCR particles in the ISM and in source region. This procedure yields at low and intermediate energy ($\geqslant$ 300 MeV/N) a path length of about 8 to 10 g cm^{-2} of interstellar matter (see e.g. Shapiro & Silberberg 1970; Garcia-Munoz *et al.* 1984, 1987; Ferrando *et al.* 1991).

(b) Energy loss of GCR heavy ions: Subiron and iron particles of low energy galactic cosmic rays (E ~ 50–200 MeV/N) suffer ionization loss while traversing ISM, and a fraction of these are reduced to energies of 1–10 MeV/N. At these energies Fe and Sc–Cr ions readily capture orbital electrons while traversing ISM or interstellar gas clouds, and a population of GCR ions of $Z > 20$ with various ionization states are produced. This is so because electron capture cross sections exceed the electron stripping cross sections by a few orders of magnitude (Biswas *et al.* 1990).

In the course of interstellar propagation a fraction of the particles in partially ionized state and with the equilibrium charge distribution, are expected to intercept the supernova remnant shock fronts in the interstellar medium. In some of these encounters, the acceleration of these heavy ions may take place. Thus, after several encounters, we expect to have a GCR population of heavy ions with equilibrium energy spectrum and with equilibrium charge distribution. These propagate in the interplanetary medium where they maintain their charged state.

4. Summary and conclusions

1. Spacelab-3 cosmic ray experiment, supported by other experiments, conclusively established that sub-iron (Sc–Cr) to iron abundance ratios in the low energy (30–300 MeV/N) galactic cosmic rays measured inside the magnetosphere are enhanced by a factor of about two as compared to their interplanetary ratios.
2. It is found that the abundance enhancement is wholly or partly due to the rigidity filtering effects of the geomagnetic field. Further experiments with higher statistical accuracy are needed to determine the degree of ionization of Sc–Cr and Fe particles in the low energy cosmic rays and these will help in understanding the details of the phenomena.
3. We suggest that in future cosmic ray detectors for sub-iron and Fe particles at low energies be flown in spacecrafts inside the magnetosphere and in the interplanetary space at the same period of time and the results therefrom can provide information on the mean ionization of the elements $Z = 21$ to 28. These, in turn, will help in understanding their propagation effects in the interplanetary medium and in the magnetosphere.

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