J. Astrophys. Astr. (1983) **4,** 197–204

Relative Abundances of Cosmic Ray Nuclei from Neon to Iron over Fort Churchill

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Received 1982 November 19; accepted 1983 August 5

Abstract. The relative abundances of the nuclei from neon to iron in the energy interval 150–400 MeV/n have been estimated by using a balloon borne cellulose-nitrate plastic detector. The source abundances are obtained by extrapolating the near-earth abundances using leaky box model of cosmic ray propagation in the interstellar space. The results are compared with those of other investigators and a general agreement is obtained. However, a discrepancy arises especially in the case of Al which is not detected in the present investigation.

Key words: cosmic rays—elemental abundances

1. Introduction

The elemental abundances of cosmic ray nuclei are of special interest since they provide unique information on the origin of cosmic rays and on the nucleosynthesis of the accelerated matter. The source composition may be deduced from the observed near-earth composition by taking into account various processes undergone by cosmic ray nuclei in the interstellar and interplanetary space in accordance with different models of cosmic ray propagation. The source abundances are closely related to the processes of nucleosynthesis and the acceleration mechanism taking place in the source region.

A number of investigations have been done in recent years on the elemental abundances of low, medium and high-energy primary cosmic rays using various detectors such as nuclear emulsions, ionisation chambers, scintillation telescopes and plastic detectors. Amongst the plastic detectors, it is the lexan polycarbonate which is widely used. But information is scanty regarding the study with cellulose nitrate detectors (Benton & Henke 1968; Tripier & Debeauvais 1977; Singh & Bhatia 1979), which is more sensitive than lexan. In the present investigation, an attempt is made to use cellulose nitrate detector in such a study.

2. Experimental procedure and selection criteria

We have used a stack of Daicell cellulose nitrate solid state plastic detector containing 92 sheets of dimensions 14.4 cm × 11.8 cm × 0.025 cm each and exposed to primary cosmic ray nuclei for 10.66 hours at a ceiling altitude of 2.8 gm cm^{-2} from Fort Churchill, Canada, on 1969 June 27, near solar maximum of 1968. 1969–1971 was a period of polarity reversal of the polar magnetic field of the Sun (Howard 1974). When polar magnetic field of the Sun is nearly parallel to the galactic magnetic field, galactic cosmic rays could intrude more easily into the heliomagnetosphere along magnetic lines of force. There has been no other published work based on this tack so far.

The plastic sheets were chemically etched in a solution of 6.25 (N) NaOH for 4 hours at $(40 \pm 0.2)^{o}$C. After successful etching, each plastic sheet has been examined under an optical microscope with a magnification of ~ 700 × to look for the presence of cones *i.e.* the sites of radiation damages produced by the cosmic ray nuclei while passing through the sheets.

The selection criterion applied is that only the cones having dip angles lying between 20° and 80° are used in the analysis. This excludes the particles travelling unduly long distances to reach the detector and also those crossing the detector almost normally. Starting from the upper sheet, each cone is followed through the successive lower sheets till the end. The necessary measurements of the cone parameters are done with a Carl Zeiss eye-piece micrometer having a least count of 0.2 μm. No measurements of the cone parameters are done for the particles leaving the detector. Also, particles producing single cone are not included in the observed sample.

3. Data analysis

An area of 20 cm^2 of each sheet has been scanned and a total of 300 particles are collected from the scanning of such sheets. From the data obtained on cone parameters such as the projected cone length, the semiminor axis of the ellipse, the radius of the sphere at the stopping point of the track, the depth of the tip of the cone from the surface of the sheet, the true cone length (L) is calculated by making use of the relation given by Henke & Benton (1971). The residual ranges corresponding to each cone length are also calculated. The different values of the residual ranges (R) obtained are plotted in Fig. 1 against the cone length (L). The different nuclei are identified by drawing LJ calibration curve as shown in Fig. 2 (see Price, Fleisher & Walker 1975). The energies of the different nuclei are obtained using the range-energy relation given by Benton & Henke (1968). Corrections are applied for scanning loss as well as for those due to interactions and ionisation processes occuring in air and in the plastic detector.

The groups of points corresponding to different nuclear charges can clearly be traced in Fig. 1. The first group of points corresponds to carbon (Z = 6). The groups corresponding to charges Z = 8, 14, 26 are easily identifiable because of the comparatively lower abundance of the nuclei of charges 9, 15, 27 and higher.

Now, the cone length (L) is a function of primary ionization J. The value of J is given by McClure (1953) as,

$$J = \frac{AZ^*}{\beta^2}\left[\ln\frac{\beta^2}{1-\beta^2} + K - \beta^2 + \delta(\beta)\right], \tag{1}$$

Where Z^* is the effective charge and is given by

$$Z^* = Z\left[1 - \exp\left(-\frac{130\beta}{Z^{2/3}}\right)\right], \tag{2}$$

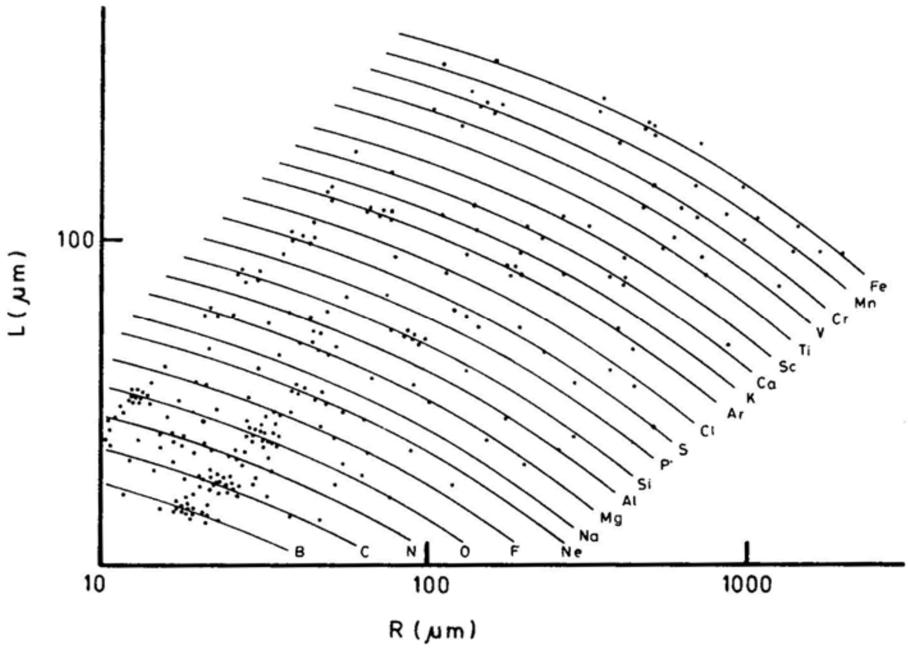

Figure 1. Plot of cone length (L) versus residual range (R).

A is a constant which depends upon the nature of the medium through which the particle passes, K is a constant and should be suitably chosen to get a proper fit to experimental data, and is β the velocity of the particle relative to that of light; $\delta(\beta)$ is the relativistic term and is zero for $\delta \leqslant 0.8$

Various values of K were tried and a smooth curve passing through the points corresponding to all the four values of charge was obtained for $K = 12$. The plot of L versus J for this value of K is shown in Fig. 2. Using this curve, we have calculated the corresponding L versus R curves for the most abundant isotopes of various charges upto Z = 26. These are shown in Fig. 1 as solid lines and are seen to yield good agreement with the experimental points for all values of charge.

4. Calculation of fluxes and discussions

The differential flux of the nuclear charge Z over the energy interval E and $E + \Delta E$ is obtained by using the relation,

$$\left(\frac{dJ}{dE}\right)_Z = \frac{N_Z}{A\Omega t \Delta E}, \tag{3}$$

where N_z is the number of particles of charge Z, t is the exposure time (10.66 hr in our experiment), $A\Omega$ is the geometrical factor for the stack, and ΔE is the energy interval (assumed to be 20 MeV/n).

The differential energy spectra of Ne, Mg and Si, the most abundant nuclei in the

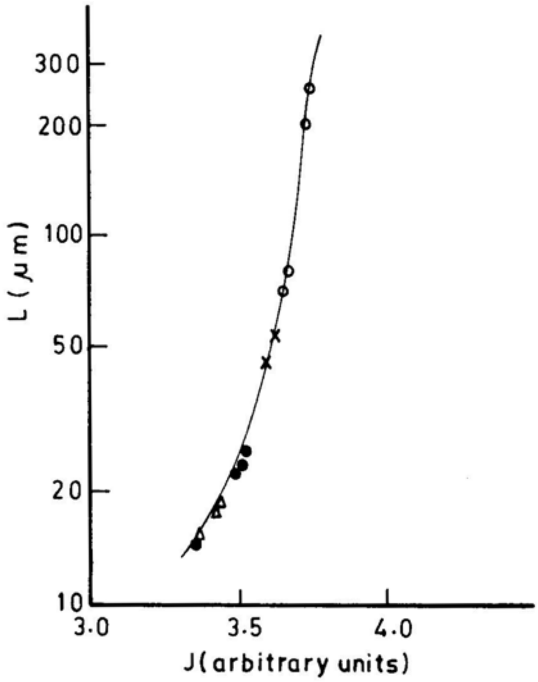

Figure 2. *L–J* (Calibration curve). Triangles: carbon; filled circles: oxygen; crosses: magnesium; open circles: iron.

range$10 \leqslant Z \leqslant 26$ are shown in Fig. 3. The continuous curves represent the near-earth spectra of these nuclei calculated on the basis of a Fermi-type of source spectrum (Ramadurai & Biswas 1974) and the nested leaky box model (Cowsik & Wilson 1975) of cosmic ray propagation. For the Fermi-type spectrum, we used the source parameters as given by Ramadurai & Biswas (1974). In the propagation calculation involving the leaky box model, we assumed a leakage mean free path in the source region $\lambda s = 1.0$ gmcm^{-2} and a leakage mean free path in the Galaxy $\lambda_G = 5.0$ gm cm $^{-2}$. The normalised probability $P(x)$ for a particle to reach near earth after a traversal of x gm cm$_{-2}$ of interstellar matter is then given by,

$$P(x) = \tfrac{1}{4}[\exp(-x/5) - \exp(-x)]. \tag{4}$$

We assumed that the interstellar space contains only hydrogen and used a range-energy relation of the type,

$$E = C(E, Z)X^{n(E)}. \tag{5}$$

To account for the fragmentation, we used the partial cross-sections given by Silberberg & Tsao (1973) for p-nucleus collisions at proton energy 400 MeV/n. After several trials, a source composition is obtained which yielded the near-earth abundances in agreement with the experimental results.

As a plastic detector is sensitive to various charges at different energy intervals, the fluxes must be normalised for a standard energy interval common to all charges. Fluxes of all such nuclei from neon to iron were normalised to the standard energy interval

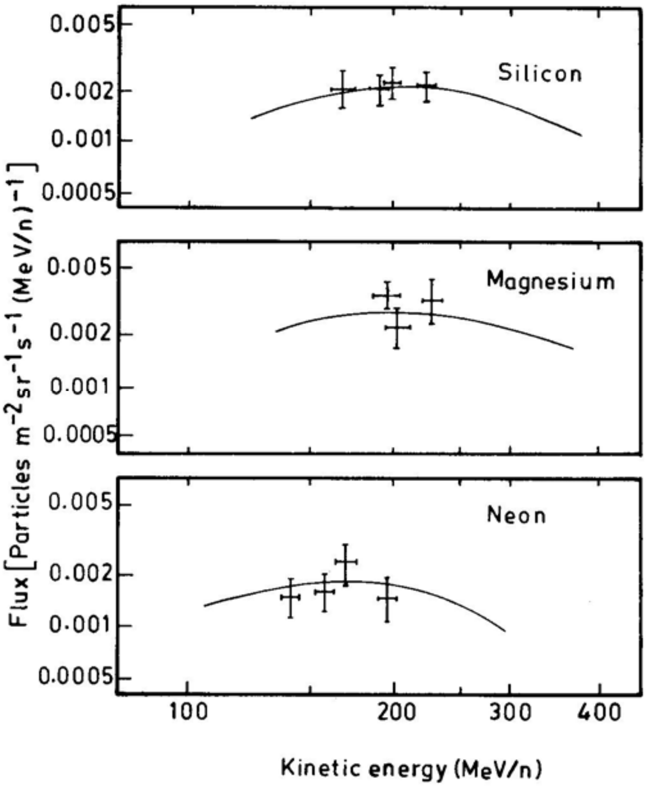

Figure 3. Differential energy spectra of Ne, Mg and Si.

150–400 MeV/n by making use of the experimentally obtained fluxes. The flux values are given in Table 1. From this table, the ratio of the abundances of all the even-Znuclei to that of all the odd-Z nuclei for $10 \leqslant Z \leqslant 26$ comes out to be approximately 4.0.

The assumed source abundances of more abundant nuclei such as Ne, Mg, Si and Fe are not very sensitive to the choice of propagation models and path lengths. A similar conclusion is arrived at by Bhatia & Singh (1979).

In Table 2, we compare the relative abundances of nuclei obtained in the present investigation, with those obtained by other investigators using different types of detectors at different periods. To facilitate the comparison, the abundances derived in similar energy intervals have been normalised to silicon taken as 100. We have compared in Fig. 4 the relative abundances obtained in the present work, with those obtained by Cartwright, Garcia-Munoz & Simpson (1971), Fisher *et al.* (1976) and Singh & Bhatia (1979). Our data are in agreement with those of the above authors. However, some discrepancy appears in a detailed comparison; for example, less abundant elements like Al, CI, K and Sc are found to be absent in our observed sample whereas others have found them to a significant level (particularly in the case of Al). We do not find any significant high abundance though the detector was exposed during a period of polarity reversal of the magnetic field of the Sun. A further study is necessary to confirm these observations.

Table 1. Differential fluxes on top of the atmosphere (150400 MeV/n).

Nuclei	Atomic no.	Flux Particles $m^{-2}\,sr^{-1}\,s^{-1}\,(MeV/n)^{-1}$
Ne	10	0.246 ± 0.021
Na	11	0.073 ± 0.012
Mg	12	0.305 ± 0.021
Si	14	0.232 ± 0.022
P	15	0.075 ± 0.011
S	16	0.058 ± 0.021
Ar	18	0.014 ± 0.009
Ca	20	0.058 ± 0.015
Ti	22	0.043 ± 0.017
V	23	0.014 ± 0.008
Cr	24	0.029 ± 0.019
Mn	25	0.013 ± 0.011
Fe	26	0.057 ± 0.032

Table 2. Relative abundances of cosmic ray nuclei ($10 \leqslant Z \leqslant 26$) normalised to silicon (= 100).

Nuclei	Energy MeV/n	150–400 (a)	100–300 (b)	150–450 (c)	72–450 (d)	200–650 (e)	350–600 (f)
Ne		106.25	117.0		104.0	102.5	114.3
Na		31.25	29.2			48.5	30.0
Mg		131.3	142.0		136.0	116.5	142.9
Al			29.2			27.1	25.7
Si		100	100	100	100	100	100
P		6.3	7.5	22.5	2.7	13.1	7.9
S		25.00	19.2	4.9	15.9	28.6	22.9
Cl			3.3	11.9	2.9	6.1	5.0
Ar		6.0	8.3	13.2	5.8	13.9	8.6
K			5.8	0.9	4.2	2.3	5.0
Ca		25.0	15.0	34.0	13.3	19.1	15.0
Sc			3.3	17.0	2.5	8.2	2.9
Ti		18.8	15.8	35.7	9.5	31.3	10.0
V		6.3	6.7	10.2	5.0	11.4	3.6
Cr		12.6	20.0	34.5	8.9	17.5	10.7
Mn		6			5.1	6.1	8.6
			91.7	82.6			
Fe		68.8			57.1	58.7	55.7

References:
(a) Present work
(b) Cartwright, GarciaMunoz & Simpson (1971)
(c) Bartholoma, Enge & Fukui (1972)
(d) GarciaMunoz, Mason & Simpson (1977)
(e) Singh & Bhatia (1979)
(f) Fisher *et al.* (1976)

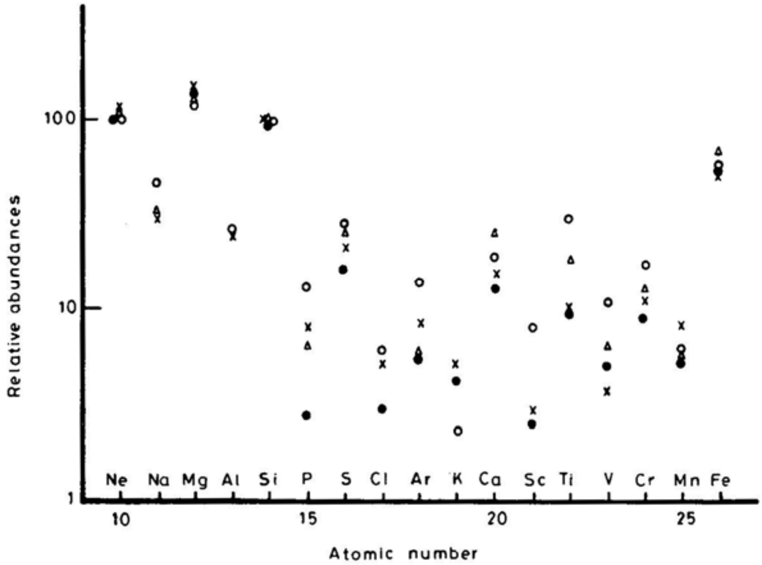

Figure 4. Relative abundance versus atomic number. Triangles: present work; closed circles: Garcia-Munoz, Mason & Simpson (1977) open circle: Singh & Bhatia (1979); crosses: Fisher *et al.* (1976).

Acknowledgements

The authors are very much grateful to Professor S. Biswas of TIFR for providing the stack as a gift and also for extending the facilities of etching the stack in the TIFR laboratory. The valuable comments received from Dr N. Durgaprasad (TIFR) and Dr J. N. Goswami (PRL) are also acknowledged. Thanks are also due to Mr P. J. Kajarekar (TIFR) for his help in etching the plastic sheets and to Mr R. Medhi for scanning the sheets. Financial assistance from UGC is also gratefully acknowledged:

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