1991ICRC....2...21M

GALACTIC PROPAGATION AND SOURCE COMPOSITION OF HIGH ENERGY COSMIC RAYS

Peter Meyer, John Grunsfeld*, Jacques L'Heureux†,
Dietrich Müller and Simon P. Swordy
The University of Chicago, Chicago, IL 60637, USA

Introduction. Almost two decades ago measurements of the elemental composition of cosmic rays of energies above a few GeV/amu have shown that the ratio of secondary to primary cosmic rays decreases with energy[1]. This result is interpreted as a decrease of the escape mean free path from the galaxy with increasing energy. To understand cosmic ray propagation in the galaxy, it is essential to learn whether this behavior extends to much higher energy, perhaps reaching the "knee" in the all particle spectrum around 10^{15} eV/particle. Our investigation, performed in 1985 on the Space Shuttle attempts to address this question.

The scientific goals of this investigation are to establish:

- the simplest propagation model consistent with the observed results
- the energy spectra at the particle sources up to TeV energies
- any anomalies in spectra or composition as one approaches the highest energies
- the source abundances of high energy cosmic rays relative to solar system abundances.

Our instrument, the Cosmic Ray Nuclei detector (CRN) on Spacelab–2 was designed to measure the elemental composition of heavy cosmic ray nuclei ($Z \geq 5$) up to energies of several TeV/amu. The upper limit in energy reached in the measurement is not imposed by the dynamic range of the instrument, rather it is due to the limit in statistical accuracy that was obtainable in 78 hours of useful exposure during a flight of 8 days that had to simultaneously accommodate a variety of other experimental requirements. Detailed descriptions of the design and performance of CRN have been previously presented and published[2].

Analysis and Results. We had previously reported results from this work[3,4], but have since improved the analysis in significant ways. The observable number of events has been increased by admitting particles from a larger aperture than was initially imposed and thus the statistical accuracy was improved. We have been able to determine absolute particle fluxes by careful examination and consideration of all corrections (see Müller et al. OG 6.1.12).

The simplest model to describe cosmic ray propagation and containment in the galaxy is the homogeneous leaky box model that includes the energy dependent escape mean free path. The escape mean free path and its rigidity dependence have been deduced from the measurement of the relative abundances of secondary and primary cosmic rays and specifically the B/C ratio[4]. Our data are consistent with a powerlaw in rigidity for the escape pathlength $\lambda_{\rm esc}$ of the form $\lambda_{\rm esc} \sim R^{-0.6}$ to the highest rigidities observed. There is no indication that a more complex propagation model is required to achieve a better match with the presently available data. Using this behavior of $\lambda_{\rm esc}$ we can extrapolate our data to the sources. At the high energies that we deal with here the propagation calculation is particularly simple since we may neglect effects of solar modulation, of ionization losses, and energy dependence of the interaction cross sections. We also neglect the possibility of energy gains representing distributed acceleration.

The total mean free path is determined by the interaction mean free path λ_i and the escape mean free path λ_{esc}

$$\frac{1}{\lambda_{\mathrm{total}}} = \frac{1}{\lambda_i} + \frac{1}{\lambda_{\mathrm{esc}}}.$$

For higher energies λ_i does not vary with energy and can be derived from the nuclear spallation cross sections[5] If the source spectrum can be represented by a power law $\sim E^{-\Gamma}$, and $\lambda_{\mathrm{esc}} \sim E^{-\delta}$, the observed spectrum of the primary nuclei at high energy ($\lambda_i >> \lambda_{\mathrm{esc}}$), becomes $N(E) \sim E^{-(\Gamma+\delta)}$. At low and intermediate energies the spectral shape varies with energy according to the change of λ_{total}. Fig. 1 shows as filled squares the measured fluxes for 6 primary nuclei at energies between 50 and 1000 GeV/amu. The solid line is the result of the propagation calculation assuming (1) that the relative elemental abundances at the sources are the same as those obtained in the work of Hinshaw and Wiedenbeck[6] for much lower energies (except for Fe which had to be corrected upwards by $\sim$ 15% and Ne which was corrected upward by 20%); (2) that the source spectra of all nuclei follow a powerlaw $\sim E^{-2.2}$. The dashed lines correspond to $E^{-2.1}$ and $E^{-2.3}$ respectively.

The observed spectra are well described by the calculations, with few exceptions (i.e. silicon) that may be statistical in origin. Our measurements also agree with previous measurements at lower energies (a detailed comparison with the work of other authors is given in ref. 7. Fig. 1 also shows the changes in spectral slopes (most pronounced for high Z particles where λ_i is smallest) that occur between 40 and 1000 GeV/amu.

In an extension of our earlier work on the energy dependence of the secondary to primary intensity ratios[4], we investigated the abundances of S, A and Ca with respect to the iron group nuclei. The results are shown in Fig. 2. The flux of these elements that arrives at Earth has a significant contribution of secondary nuclei. Hence, their ratios with respect to iron decrease with energy, and the observation extends the energy dependence of the secondary/primary ratio to heavy nuclei. Also shown are two results from the HEAO-3 experiments of Engelmann et al[8]

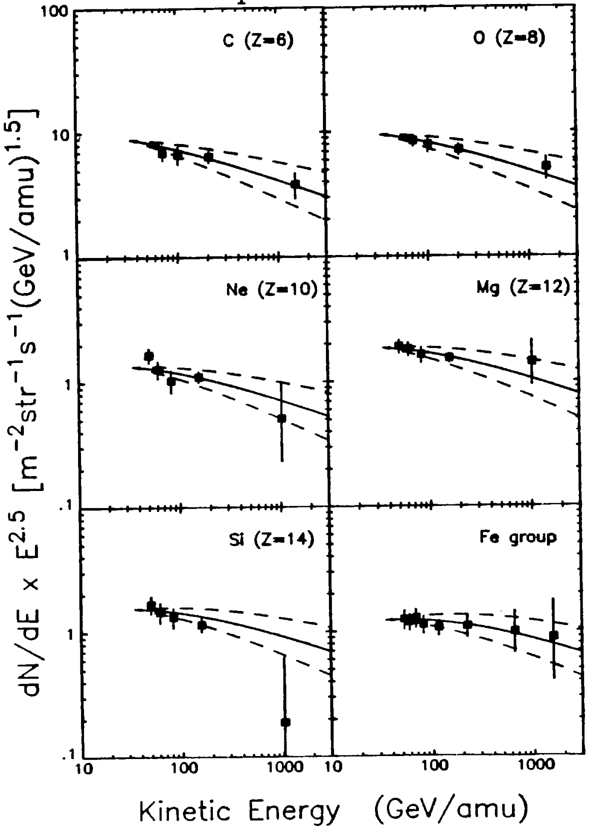

Figure 1: *Measured energy spectra of 6 primary nuclei. Curves: propagation calculation with source* $\sim E^{-2.2}$ *(solid);* $\sim E^{2.1}$ *(upper dashed);* $\sim E^{-2.3}$ *(lower dashed).*

(solid triangles) and Binns et al[9] (open squares). Extrapolations of the Engelmann et al results fit very well with our data points (full circles). The shaded regions are the range of expected abundance ratios in the sources as calculated by Hinshaw and Wiedenbeck[6] for sulfur, and by Binns et al[9] for argon and calcium. Our lowest energy points were obtained using the geomagnetic field. The spacecraft orbit covers a wide range of geomagnetic latitudes and the geomagnetic cutoff is used to determine an integral flux for the spectrum.

At lower energies it is well established, although not fully understood, that the source abundances of cosmic rays relative to the local interstellar abundances show a systematic dependence on the first ionization potential (FIP) of the element in question[10]. This phenomenon has been observed for cosmic rays, at all atomic numbers and also for the average of energetic solar flare particles. Exceptions are the two abundant nuclei H and He. The FIP dependence has been interpreted as due to a fractionation according to atomic properties and points to a similarity of the nature of the samples and of the acceleration mechanisms that act on them. Our experiment permits an extension of the study of the phenomenon to higher energies than had been possible in the past. The result of this investigation is seen in Fig. 3 where we plot the FIP dependence of the ratio of the galactic cosmic ray source (GCRS) abundances to the local galactic abundances (LG) for three energy intervals. Panel 1 is from Koch-Miramond[11]. The panels at 100 GeV/amu and 1 TeV/amu are from this experiment. The ratio at Fe is normalized to 1. The similarity of the FIP dependence over 3 orders of magnitude in energy is striking and one may conclude that the cosmic rays over the entire range of energy underwent the same fractionation and hence are of similar origin.

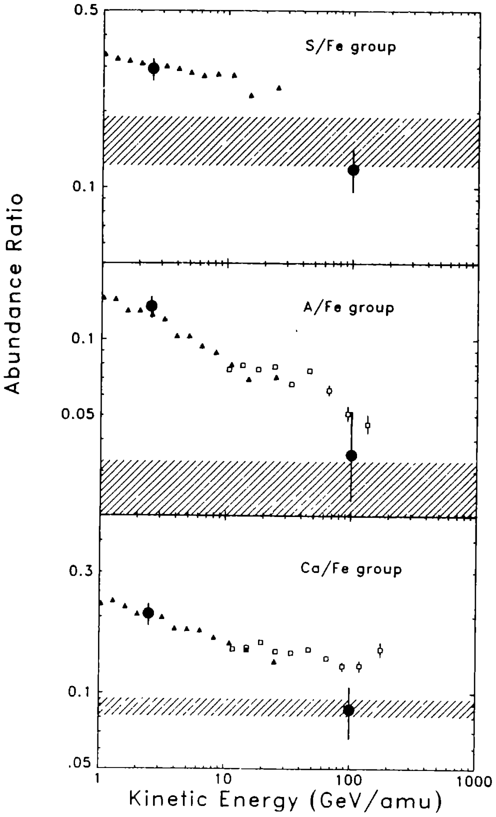

Figure 2: *S/Fe, A/Fe and Ca/Fe as a function of energy. Shaded regions are estimates for source abundance ratios.*

Summary and Conclusions. In a new analysis of the results on the elemental composition of cosmic rays at high energies, as measured on Spacelab-2 we were able to increase the body of data and improve statistical accuracy. We were also able to determine absolute fluxes and spectra for individual elements.

The ratio of secondary to primary particles as a function of energy yields the rigidity dependence of the escape mean free path as a powerlaw $\lambda_{\rm esc} \sim R^{-0.6\pm0.1}$. The simple leaky box model of propagation with this rigidity dependent $\lambda_{\rm esc}$ describes the measured spectra, with an elemental abundance distribution in the sources that is the same as found at lower energies, and of source spectra that are powerlaws of the form $\sim E^{-2.2\pm0.1}$. No changes in the rigidity dependence of either λ_{esc}, or the source spectra are noticed as the energy approaches several TeV/amu. The relative source abundances of the cosmic ray nuclei exhibit the same FIP dependence at 100 GeV/amu and at 1 TeV/amu that is observed at 1 to 25 GeV/amu. One may conclude that the particles that populate the high energy part of the spectrum have undergone the same atomic fractionation, and hence are of similar origin as those of much lower energy.

This work was supported by NASA under contract NAS 8–32828 and grants NAG W-1311, NGL 14–001–005 and NGL 14–001–258.

REFERENCES.

1. Juliusson, E., Meyer, P., and Müller, D. (1972), *Phys. Rev. Letters* **29**, 445.
2. L'Heureux, J., Grunsfeld, J.M., , Meyer, P., Müller, D. and Swordy, S.P. (1990), *NIM* **A295**, 246.
3. Grunsfeld, J.M., , L'Heureux, J., Meyer, P., Müller, D. and Swordy, S.P. (1988), *Ap. J.* **327**, L31.
4. Swordy, S.P., Müller, D., Meyer, P., L'Heureux, J. and Grunsfeld, J.M., (1990), *Ap. J.* **349**, 625.
5. Tsao, C.H. and Silberberg, R. (1979), *Proc. 16th ICRC (Kyoto)* **2**, 202.
6. Hinshaw, G.F. and Wiedenbeck, M.E. (1983), *Proc. 18th ICRC (Bangalore)* **9**, 263.
7. Müller, D., Swordy, S.P., Meyer, P., L'Heureux, J. and Grunsfeld, J.M., (1991), *Ap. J.* **374**, 356.
8. Engelmann, J.J., Goret, P., Juliusson, E., Koch-Miramond, L., Masse, P., Soutoul, A., Byrnak, B., Lund, N., Peters, B., Rasmussen, I.K., Rotenberg, M., Westergaard, N.J. (1983), *Proc. 18th ICRC (Bangalore)* **2**, 17.
9. Binns, W.R., Garrard, T.L., Israel, M.H., Jones, M.D., Kamionkowski, M.P., Klarmann, J., Stone, E.C. and Waddington, C.J. (1988), *Ap. J.* **324**, 1106.
10. Meyer, J.P. (1985), *Ap. J. Suppl.* **57**, 173.
11. Koch-Miramond, L. (1981), *Proc. 17th ICRC (Paris)* **12**, 21.

* Now at California Institute of Technology, Pasadena, CA 91125, USA.

† Now at Bartol Research Institute, Univ. of Delaware, Newark, DE 19716, USA.

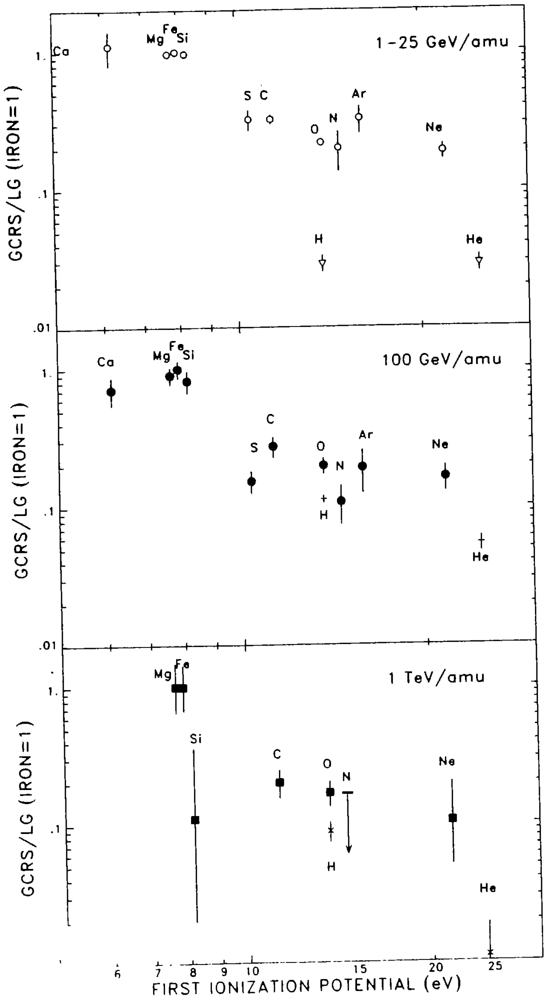

Figure 3: *FIP dependence of the cosmic ray source abundance relative to the local galactic abundance. Upper panel from Koch-Miramond*[11]*. Middle and lower panel from this experiment.*