$\alpha = 1$ and 630 GeV/N for $\alpha = 2$. Furthermore it would become difficult to account for the isotropy of the high energy cosmic ray flux[2].

Thus the fluxes of secondary elements determined at such high energies are of great aid in distinguishing between models of disk confinement and halo confinement. This is particularly important now that the half life of ^{10}Be has been shown to be too short to be of real relevance to this problem[15].

In conclusion a reasonable extrapolation of the observations of Juliusson *et al.*[1] implies that, if the high energy ($E \gtrsim 2 \times 10^4$ GeV/N) cosmic rays are galactic, they are trapped in regions much larger than the galactic disk. Otherwise, it is possible that these high energy cosmic rays are of extra-galactic origin.

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[1] Juliusson, E., Meyer, P., and Müller, D., *Phys. Rev. Lett.*, **29**, 445 (1972).
[2] Ginzburg, V. L., and Syrovatskii, S. I., *The Origin of Cosmic Rays* (Pergamon Press, Oxford, 1964).
[3] Meneguzzi, M., Audouze, J., and Reeves, H., *Astron. Astrophys.*, **15**, 337 (1971).
[4] Buffington, A., Smith, L. H., and Smooth, G., in *Proc. Twelfth Intern. Conf. Cosmic Rays, Hobart*, 1971 (edit. by Fenton, A. G., and Fenton, K. B.), **1**, 147 (University of Tasmania, 1972).
[5] Cartwright, B. G., Garcia-Munoz, M., and Simpson, J. A., in *Proc. Twelfth Intern. Conf. Cosmic Rays, Hobart*, 1971 (edit. by Fenton, A. G., and Fenton, K. B.), **1**, 215 (University of Tasmania, 1972).
[6] Webber, W. R., Damle, S. V., and Kish, J., *Astrophys. Space Sci.*, **15**, 245 (1972).
[7] Casse, M., Koch, L., Lund, N., Meyer, J. P., Peters, B., Soutoul, A., and Tandon, S. N., in *Proc. Twelfth Intern. Conf. Cosmic Rays, Hobart*, 1971 (edit. by Fenton, A. G., and Fenton, K. B.), **1**, 241 (University of Tasmania, 1972).
[8] Saito, T., *J. Phys. Soc. Jap.*, **30**, 1243 (1971).
[9] Saito, T., *J. Phys. Soc. Jap.*, **30**, 1535 (1971).
[10] Shapiro, M. M., and Silberberg, R., *Ann. Rev. Nucl. Sci.*, **20**, 323 (1970).
[11] Shapiro, M. M., Silberberg, R., and Tsao, C. H., in *Proc. Twelfth Intern. Conf. Cosmic Rays, Hobart*, 1971 (edit. by Fenton A. G., and Fenton, K. B.), **1**, 221 (University of Tasmania, 1972).
[12] Cachon, A., *Fifth Inter-American Sem. Cosmic Rays*, **2**, 39 (1962).
[13] Jokipii, J. R., and Parker, E. N., *Astrophys. J.*, **155**, 799 (1969).
[14] Jones, F. C., *Astrophys. J.*, **169**, 447 (1971).
[15] Yiou, F., and Raisbeck, G., *Phys. Rev. Lett.*, **29**, 372 (1972).

Energy Dependence of Primary Cosmic Ray Nuclei Abundance Ratios

RECENT measurements of cosmic ray chemical composition between 1 and 100 GeV nucleon^{-1} (refs 1–3) show a decrease of the abundance ratios of secondary to parent nuclei above $\simeq 10$ GeV/N. This suggests that above this energy the mean path length of cosmic rays decreases with increasing energy[3,4]. Indeed, the variations of the abundance ratios $\frac{17 \leq Z \leq 25}{\text{Fe Ni}}$ and $\frac{\text{Li Be B}}{\text{C O}}$ imply a decrease of the mean path length from several g cm^{-2} at $E \simeq 2$ GeV/N to a fraction of a gram at $E \simeq 100$ GeV/N.

The same observations also show an energy dependence of the primary nuclei abundance ratios. The presently observed variations of these ratios seem to be consistent with (and give more support to) the conclusion drawn from secondary to parent nuclei ratios, without any need for additional hypothesis, such as charge dependence of the mean path length or charge dependence of the source spectral index.

I take as an example two nuclear species i and j emitted by cosmic ray sources, with the same spectral index, and assume an exponential path length distribution (justified by studies at GeV energies[5]); their abundance ratio at a few GeV/N is given by

$$\frac{N_i}{N_j} = \left(\frac{N_i}{N_j}\right)_{\text{source}} \frac{\dfrac{1}{\lambda_j} + \dfrac{1}{\lambda}}{\dfrac{1}{\lambda_i} + \dfrac{1}{\lambda}} \qquad (1)$$

where λ is the cosmic ray escape length (or mean path length) at this energy, and λ_i and λ_j are the nuclear destruction path lengths. If λ decreases with increasing energy, the second factor on the right hand of equation (1) approaches one when escape dominates nuclear destruction, that is, when λ reaches a fraction of a g cm^{-2}. Therefore, if the conclusion of the first paragraph is correct, I expect $\frac{N_i}{N_j}$ to decrease by a factor

$$\frac{\dfrac{1}{\lambda_j} + \dfrac{1}{\lambda(2\ \text{GeV/N})}}{\dfrac{1}{\lambda_i} + \dfrac{1}{\lambda(2\ \text{GeV/N})}}$$

between $E \simeq 2$ GeV/N and $E \simeq 100$ GeV/N, and to become nearly equal to the source value at $E \simeq 100$ GeV/N.

Table 1 Expected and Measured Abundance Ratios

Abundance ratios	$E \simeq 2$ GeV/N	$E \gtrsim 50$ GeV/N	Reduction factor	Expected reduction factor	Calculated source ratio[7]
$\frac{\text{C O}}{\text{Fe Ni}}$	20 ± 3 (refs. 1–3)	8 ± 5 (ref. 1)	2.5 ± 1.4	1.8	8.2
		7 ± 2 (ref. 2)	2.9 ± 0.8		
$\frac{\text{He}}{\text{Fe Ni}}$	330 ± 60 (ref. 1)	160 ± 100 (ref. 1)	2 ± 1.4	2.5	110
$\frac{\text{He}}{\text{C O}}$	20 ± 2 (ref. 1)	20 ± 9 (ref. 1)	0.7 ± 0.3	1.3	13.5

Applying this calculation to the ratios $\frac{\text{C O}}{\text{Fe Ni}}$, $\frac{\text{He}}{\text{Fe Ni}}$ and $\frac{\text{He}}{\text{C O}}$ with $\lambda \simeq 7$ g cm^{-2} of interstellar matter (using the technique of ref. 5) and with nuclear destruction path lengths of respectively 16.2, 7.2 and 2.8 g cm^{-2} for He, CO and Fe (with 90% H and 10% He in interstellar matter), I find that these ratios must decrease by factors 1.8, 2.5 and 1.3 respectively. Table 1 shows a comparison between the expected and measured variations of these ratios with energy. The agreement is good for $\frac{\mathrm{C\,O}}{\mathrm{Fe\,Ni}}$ and $\frac{\mathrm{He}}{\mathrm{Fe\,Ni}}$ and the value above 50 GeV/N agrees with the calculated source values[7]. But the $\frac{\mathrm{He}}{\mathrm{C\,O}}$ value reported by Smith *et al.*[1] seems to increase slightly with energy, contrary to expectation.

In view of the experimental uncertainties, and because $\frac{\mathrm{C\,O}}{\mathrm{Fe\,Ni}}$ and $\frac{\mathrm{He}}{\mathrm{Fe\,Ni}}$ are more sensitive than $\frac{\mathrm{He}}{\mathrm{C\,O}}$ to escape length variations, I conclude that the present observed energy dependence of the primary nuclei abundance ratios seems to be consistent with the result derived from secondary to parent ratios, that is, with a decrease of the cosmic ray escape length from $\simeq 7$ g cm^{-2} at $\simeq 2$ GeV/N to < 1 g cm^{-2} at $\simeq 100$ GeV/N, implying poor confinement of cosmic rays in the Galaxy above this energy.

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[1] Smith, L. H., Buffington, A., Smoot, G. F., Alvarez, L. W., and Wahlig, W. A., *Berkeley Space Sciences Laboratory Publ.*, Series 13, Issue 69 (1972).

[2] Juliusson, E., Meyer, P., and Muller, D., *Phys. Rev. Lett.*, **29**, 445 (1972).

[3] Webber, W. R., Lezniak, J. A., Kish, J. C., and Damle, S. V., *Nature Physical Science*, **241**, 96 (1973).

[4] Audouze, J., and Cesarsky, C., *Nature Physical Science*, **241**, 98 (1973).

[5] Shapiro, M. M., and Silberberg, R., *Ann. Rev. Nucl. Sci.*, **20**, 323 (1970).

[6] Meneguzzi, M., Audouze, J., and Reeves, H., *Astron. Astrophys.*, **15**, 337 (1971).

[7] Shapiro, M. M., Silberberg, R., and Tsao, C. H., *Proc. Twelfth Internat. Symp. Cosmic Rays* (Hobart, 1971).

Viscosity of Basic Magmas at Varying Pressure

THE viscosity of magmas is an important parameter in problems concerning the generation and emplacement of magmatic rocks[1,2], but no experimental data exist on hydrous basaltic melts. Here I describe laboratory determinations of the viscosity of some basic melts at one atmosphere and at high water pressures and their relationship to melt chemistry[3]. Basic rocks ranging in composition from basic andesite to olivine melanephelinite had viscosities between 4,000 – 100 ($\pm 5\%$) poise at temperatures near the liquidus (1,200° C) at one atmosphere. At higher temperatures (1,400° C) viscosities ranged from 260 – 15 ($\pm 5\%$) poise (Fig. 1). These results are in fair agreement with previous work using a concentric-cylinder method[4–9]. I also found, in agreement with previous work[9,10], that the redox state of basic melts had only a marginal effect on viscosities.

Viscosity was related to composition by an index $R = \mathrm{O}/(\mathrm{Si}+\mathrm{Al}+\mathrm{P})$ which indicates the ratio of the molecular per cent of non-bridging oxygens to network-forming cations[11–13]. Basalts and ultrabasic compositions had R values between 2.2–3.5 (granite compositions had low R values near 2). Construction of a viscosity-temperature-R grid (Fig. 2) made it possible to predict viscosities of melts or supercooled lavas of unknown viscosity from a knowledge of their chemistry and hence their R value. For example, a melt of picritic composition had calculated viscosities of ~ 40 poise at 1,300° C and at one atmosphere.

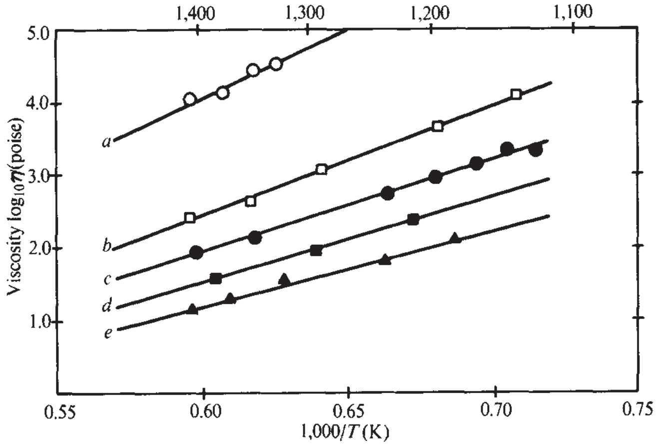

Fig. 1 Plot of $\log_{10}\eta$ against $1{,}000/T$ K for results from viscosity measurements using a concentric-cylinder viscometer at one atmosphere in air. Compositions: *a*, pantellerite (for comparison); *b*, basic andesite; *c*, oceanic island tholeiite; *d*, olivine basalt; *e*, olivine melanephelinite. Each point represents several determinations at different rotational speeds.

Activation energies for viscous flow of melts at liquidus temperatures ($\sim$ 1,200° C) at one atmosphere pressure decreased with increasing R value (Fig. 3) suggesting that ultrabasic melts were the least polymerized of natural melts[14]. Measurements performed using a fibre-extension viscometer gave activation energies for supercooled lavas between 650–750° C which were 2–3 times the activation energies at 1,200° C.

The effect of dissolving 4 ± 0.5 wt % H_2O in basaltic melts under $P_{H_2O} = 1$ kbar was to lower viscosities compared to the viscosities of dry melts at one atmosphere. As measured by falling-sphere viscometry, the viscosity of a melt of basic andesite composition (*b*) at 1,150° C was lowered from 10,000 to 2,500 ($\pm 10\%$) poise and a tholeiite melt (*c*) was lowered from 1,600 to 600 ($\pm 10\%$) poise. A melt of olivine basalt composition (*d*), however, showed no measurable reduction in viscosity. Application of these values to the viscosity-temperature-R grid, using R values calculated from the anhydrous compositions with 4 wt % H_2O added, showed that to a first

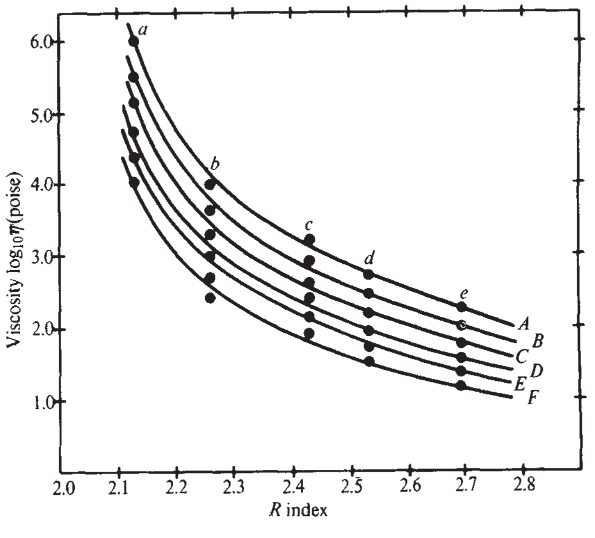

Fig. 2 Relationship between viscosity, temperature and composition at one atmosphere. Compositions as in Fig. 1. Temperatures (°C): *A*, 1,150; *B*, 1,200; *C*, 1,250; *D*, 1,300; *E*, 1,350; *F*, 1,400.