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HIGH RESOLUTION MEASUREMENTS OF GALACTIC COSMIC-RAY NEON, MAGNESIUM, AND SILICON ISOTOPES

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ABSTRACT

The individual isotopes of galactic cosmic-ray Ne, Mg, and Si at ~100 MeV per nucleon have been clearly resolved with an rms mass resolution of ~0.20 amu. Our results suggest that the cosmic-ray source is enriched in ^{22}Ne, ^{25}Mg, and ^{26}Mg when compared to the solar system. In particular, we find $(^{25}\mathrm{Mg} + ^{26}\mathrm{Mg})/^{24}\mathrm{Mg} = 0.49(+0.23, -0.14)$ compared with the solar system value of 0.27, suggesting that the cosmic-ray source and solar system material were synthesized under different conditions.

Subject headings: cosmic rays: abundances — cosmic rays: general

I. INTRODUCTION

Our present understanding of the synthesis of the elements is based mainly on the comparison of the predictions of detailed theoretical models with the observed distribution of isotopes in such primitive solar system matter as meteorites. Galactic cosmic-ray nuclei provide a sample of matter from outside the solar system, which, in view of its younger age and possible association with supernovae, may have experienced a different nucleosynthetic history. Because the elements neon, magnesium, and silicon each possess more than one relatively abundant isotope and because they are the result of several nucleosynthetic processes, they are excellent choices for investigating possible isotopic differences between the galactic cosmic-ray source and the solar system.

Neon is the first element for which there is strong evidence of an anomalous galactic cosmic-ray isotopic composition. Several recent studies (Fisher *et al.* 1976; Prezler *et al.* 1975; Garcia-Munoz, Simpson, and Wefel 1979; Greiner *et al.* 1979) find a several-fold excess of ^{22}Ne at the cosmic-ray source compared with the Cameron (1973) solar system compilation ($^{20}\mathrm{Ne}/^{22}\mathrm{Ne} = 8.2$); or to solar-flare nuclei [$^{20}\mathrm{Ne}/^{22}\mathrm{Ne} = 7.6(+2.0, -1.8)$, Mewaldt *et al.* 1979; see also Dietrich and Simpson 1979]; or to the solar wind ($^{20}\mathrm{Ne}/^{22}\mathrm{Ne} = 13.7$, Geiss 1973).

In this *Letter* we report the first cosmic-ray observations with clearly resolved individual isotopes of Ne, Mg, and Si. These observations cover the energy interval from ~30 to ~180 MeV per nucleon, where a mass resolution of $\sigma \sim 0.20$ amu is achieved. In addition to finding an excess of ^{22}Ne as in earlier studies, our observations indicate that ^{25}Mg and ^{26}Mg are possibly overabundant in the cosmic rays. After correcting for interstellar propagation and solar modulation effects, we compare the source abundances of the Ne, Mg, and Si isotopes with calculated nucleosynthesis yields.

II. THE INSTRUMENT

The Caltech Heavy Isotope Spectrometer Telescope (HIST) is carried on the *ISEE 3* spacecraft, launched 1978 August 12 into a heliocentric orbit ~0.99 AU from the Sun. The HIST telescope, described in detail by Althouse *et al.* (1978), consists of an array of solid-state detectors, including a pair of two-dimensional position-sensitive detectors which determine individual particle trajectories, thereby leading to significant improvement in isotope resolution over previous cosmic-ray instruments. The present study includes particles stopping in the last five analyzed detectors of HIST, corresponding to an energy range of ~30 to ~180 MeV per nucleon for Ne, Mg, and Si nuclei.

III. THE OBSERVATIONS

This study includes quiet-time data from 1978 August 12 to December 1. Periods of possible contamination by solar-flare nuclei have been excluded by monitoring the counting rate of $Z \geq 3$ nuclei with energies $\gtrsim 5$ MeV per nucleon.

The method of resolving isotopes in HIST has been discussed previously by Mewaldt *et al.* (1979). In this study we used the outputs of the last three triggered detectors to make two separate determinations of the charge Z and the mass M for each event. Those events for which the two mass determinations were consistent to within ±5% were accepted for further analysis and a best estimate for M was computed from a weighted average of the two individual mass determinations. Only 4 out of 124 events were eliminated by this consistency test.

Figure 1*a* shows mass histograms obtained in accelerator calibrations of HIST at the Bevalac by fragmenting an Fe beam in a polyethylene target, while Figure 1*b* shows flight data for the same energy range. Both data sets in Figure 1 have been analyzed in exactly the same manner, using identical selection criteria and instrument calibrations. The Bevalac data therefore provide absolute knowledge of the mass scale. The average mass resolution in the calibration data is $\sigma_m \approx 0.18$ amu, while in the flight data $\sigma_m \approx 0.20$ amu.

We determined the relative isotopic abundances using two-dimensional maximum likelihood techniques that take into account both mass determinations for each event. These abundances were then corrected for small energy interval differences, assuming a modulated energy spectrum at 1 AU of $dJ/dT \propto T^{0.6}$, as suggested by measurements by Garcia-Munoz *et al.* (1977). Table 1 summarizes our measured isotopic composition of galactic cosmic rays at 1 AU. In Figure 2 we compare our observations with other reported measurements, and with the expected isotopic fractions for a cosmic-ray source with solar-system isotopic composition (see § IV).

Other investigations measured the mean mass of neon (Fisher *et al.* 1976; Dwyer 1978), or the ^{22}Ne/^{20}Ne ratio (Prezler *et al.* 1975; Garcia-Munoz, Simpson, and Wefel 1979; Greiner *et al.* 1979) without determining the ^{21}Ne abundance. To include these measurements in Figure 2 we assumed a ^{21}Ne fraction of 0.11 at 1 AU, as is calculated assuming negligible ^{21}Ne at the source. Our observations are consistent with those earlier studies that find excess ^{22}Ne in the cosmic rays. The mean mass measurements of Fisher *et al.* (1976) and of Dwyer (1978) do not yield unambiguous individual isotopic abundances for Mg and Si, but their results are generally consistent with a source having solar-system isotopic composition. In contrast, our results suggest excesses of both ^{25}Mg and ^{26}Mg at the source. In addition, Simpson *et al.* (1977) have reported both

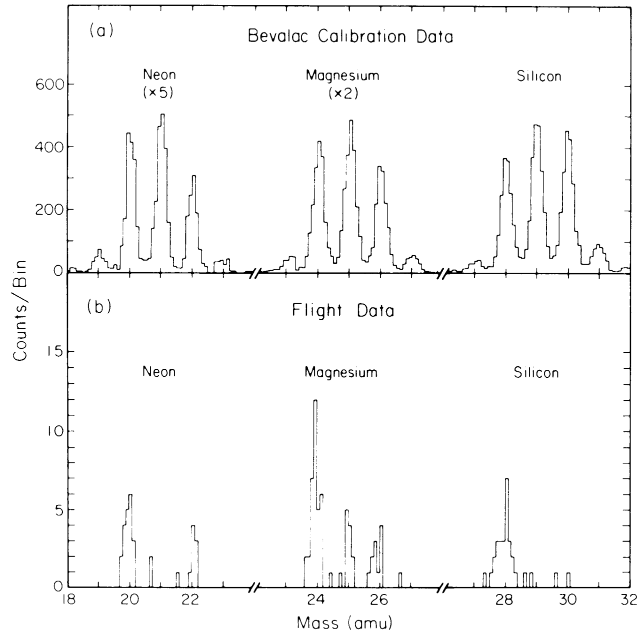

FIG. 1.—Mass histograms of (*a*) Bevalac calibration data and (*b*) flight data, for ~30 to ~180 MeV per nucleon Ne, Mg, and Si isotopes. In addition to stable isotopes, the calibration data include short-lived radioactive species.

TABLE 1

FRACTIONAL ISOTOPIC ABUNDANCES[a]

Isotope	Observed Fraction[b]	Cosmic Ray Source Fraction[b]	Solar System Fraction[c]
^{20}Ne.............	0.62 (+0.06, −0.11)	0.75 (+0.13, −0.14)	0.889
^{21}Ne.............	0.07 (+0.07, −0.03)	<0.06	0.003
^{22}Ne.............	0.31 (+0.08, −0.08)	0.25 (+0.14, −0.13)	0.108
^{24}Mg.............	0.60 (+0.04, −0.07)	0.67 (+0.07, −0.09)	0.787
^{25}Mg.............	0.19 (+0.06, −0.04)	0.16 (+0.07, −0.06)	0.101
^{26}Mg.............	0.21 (+0.06, −0.04)	0.17 (+0.08, −0.06)	0.112
^{25}Mg+^{26}Mg.......	0.40 (+0.07, −0.04)	0.33 (+0.09, −0.07)	0.213
^{28}Si..............	0.86 (+0.03, −0.11)	0.91 (+0.03, −0.12)	0.922
^{29}Si..............	0.07 (+0.07, −0.03)	0.04 (+0.08, −0.02)	0.047
^{30}Si..............	0.07 (+0.08, −0.03)	0.05 (+0.07, −0.03)	0.031
^{29}Si+^{30}Si.........	0.14 (+0.11, −0.03)	0.09 (+0.12, −0.03)	0.078

[a] The fraction relative to the total element abundance.

[b] 68% confidence intervals.

[c] Cameron 1973.

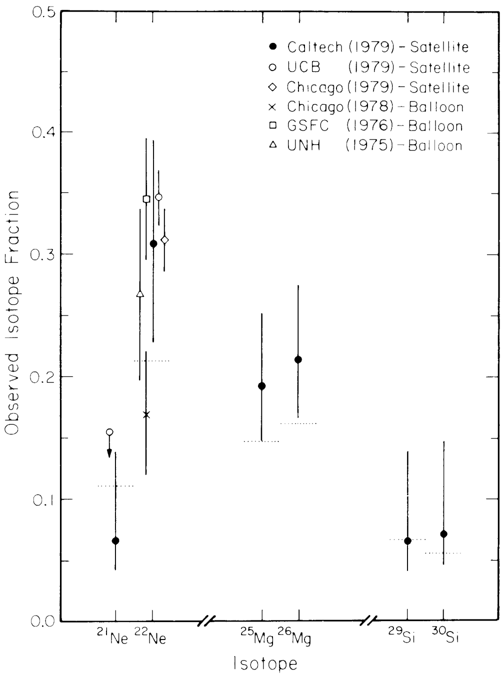

FIG. 2.—A comparison of fractional isotopic abundances. The dotted lines show the calculated fraction at 1 AU for a solar system source composition. References for the measurements: UCB (Greiner *et al.* 1979); Chicago 1979 (Garcia-Munoz, Simpson, and Wefel 1979); Chicago 1978 (Dwyer 1978); GSFC (Fisher *et al.* 1976); UNH (Prezler *et al.* 1975).

isotopic fractions and mean mass measurements for Ne, Mg, and Si at ∼3 g cm^{-2} residual atmosphere, which they concluded were consistent with a solar-system source composition.

IV. INTERPRETATION OF THE OBSERVED ISOTOPIC ABUNDANCES

In order to relate our observations at 1 AU to the cosmic-ray source composition, we performed interstellar propagation and solar modulation calculations. We assumed a standard leaky-box propagation model with a mean free path for leakage from the galaxy of $\lambda = 5.5$ g cm^{-2} (Garcia-Munoz, Mason, and Simpson 1977*a*). Fragmentation cross sections were obtained from the semi-empirical formulae of Silberberg, Tsao, and Shapiro (1976). The source abundances of elements with $6 \leq Z \leq 28$ were adjusted to fit the elemental composition measured by Garcia-Munoz, Mason, and Simpson (1977*b*), Garcia-Munoz *et al.* (1977), and Lezniak and Webber (1978). The source was assumed to have solar system isotopic composition (Cameron 1973), with the exceptions of Ne, Mg, and Si, where the isotopic fractions were allowed to vary for comparison with the observations.

In order to calculate the effect of solar modulation on the relative abundances of isotopes that differ in their charge-to-mass (Z/A) ratios, we evaluated numerical solutions of the Fokker-Planck equation (Fisk 1971). A convenient measure of the degree of solar modulation is the energy-loss parameter Φ measured in MeV per nucleon (Gleeson and Axford 1968). For a source spectrum $dJ/dT \propto (T + E_0)^{-2.6}$, where T is the kinetic energy in MeV per nucleon and E_0 is a constant, Garcia-Munoz, Mason, and Simpson (1977*a*) find $\Phi \approx$ 220 MeV per nucleon for 1973–1976 with $E_0 = 400$ MeV per nucleon. We used this spectrum and $\Phi = 300$ MeV per nucleon for late 1978. For $E_0 = 400(+200, -150)$ MeV per nucleon, and corresponding values of $\Phi = 300 \pm 100$ MeV per nucleon, we find that the 1 AU ^{22}Ne/^{20}Ne ratio at ∼100 MeV per nucleon is 19 ± 6% greater than the interstellar value at $T = (100 + \Phi)$ MeV per nucleon. Solar modulation effects on the other isotopic ratios considered here are correspondingly smaller than for ^{22}Ne/^{20}Ne.

Figure 3 shows the predicted ^{25}Mg + ^{26}Mg fraction at 1 AU as a function of the ^{25}Mg + ^{26}Mg fraction at the source for various combinations of Φ and λ, assuming that ^{26}Al (half-life = 7×10^5 yr) decays. Also indicated are the 68% (1 σ) and 90% (1.65 σ) confidence intervals, as derived from the maximum likelihood analysis. Note that our observations imply a (^{25}Mg + ^{26}Mg) source fraction of 0.33(+0.09, −0.07), significantly greater than the solar-system fraction of 0.21. Using similar curves for the individual Ne, Mg, and Si isotopes, we obtain the cosmic-ray source composition in Table 1. The uncertainties in Table 1 include statistical uncertainties in the measurements, as well as uncertainties associated with propagation and modulation (which are typically ∼0.01), as derived from the envelope of the calculated curves for $\lambda = 5.5 \pm 1$ g cm^{-2} and $\Phi = 300 \pm 100$ MeV per nucleon.

An additional uncertainty in the propagation calculations is associated with uncertainties in the fragmentation cross sections, as discussed by Stone and Wiedenbeck (1979), and by Garcia-Munoz, Simpson, and Wefel (1979) and Greiner *et al.* (1979) for the case of ^{22}Ne. The Silberberg, Tsao, and Shapiro (1976) formulae lead to approximately equal secondary contributions to all three Ne isotopes. Since the observed ^{21}Ne should be almost entirely of secondary origin, the agreement of the ^{21}Ne observations with the calculations (see Fig. 2) provides a check that the propagation model has not grossly underestimated the secondary contributions to the other nuclei. Although systematic errors in the relative cross sections are possible, we find from Stone and Wiedenbeck (1979) that systematic underestimates of a number of ^{22}Ne-production cross sections by a factor of > 3 relative to ^{21}Ne production would be required to account for the observed ^{22}Ne excess, while ^{25}Mg and ^{26}Mg excesses of a factor of ∼1.8 would require systematic cross section errors of a factor of 2–3. We feel that such large systematic errors in the relative cross sections are very unlikely.

From Table 1 and Figure 2 we note that ^{22}Ne, ^{25}Mg, and ^{26}Mg appear to be more abundant in the cosmic-ray source than in the solar system. In the case of ^{22}Ne we feel that it is significant that the direct isotope measurements (including Prezler *et al.* 1975; Garcia-Munoz, Simpson, and Wefel 1979; Greiner *et al.* 1979; and this work) all indicate an excess of ^{22}Ne, while there is disagreement among the indirect isotope measurements (Fisher *et al.* 1976; Dwyer 1978; Simpson

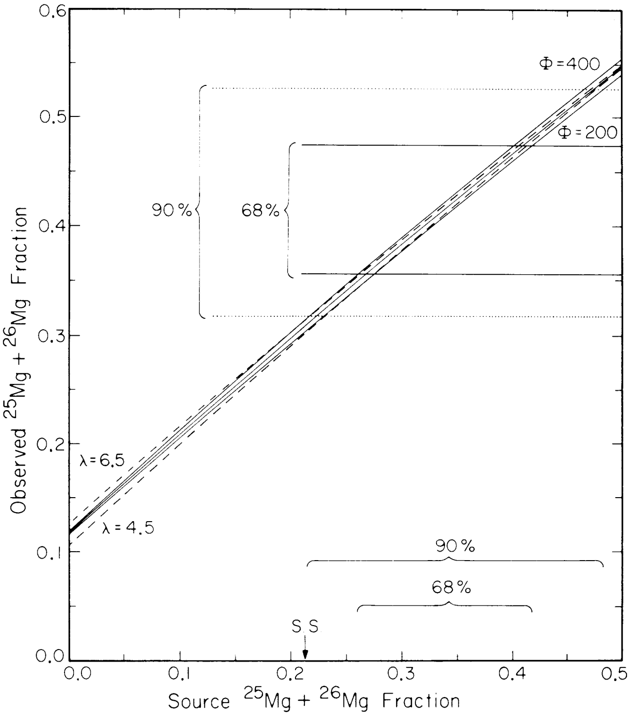

FIG. 3.—Calculations of the observed ^{25}Mg + ^{26}Mg fraction versus the ^{25}Mg + ^{26}Mg fraction at the source. The solid curves assume $\lambda = 5.5$ g cm^{-2} and $\Phi = 300 \pm 100$ MeV per nucleon. The dashed curves assume $\Phi = 300$ MeV per nucleon and $\lambda = 4.5$ and 6.5 g cm^{-2}. Confidence intervals of 68% and 90% are indicated. The arrow marked S.S. indicates the solar system fraction.

et al. 1977). For the four direct measurements shown in Figure 2, the mean observed ^{22}Ne fraction is 0.33 ± 0.02, corresponding to a source fraction of 0.27 ± 0.03, and a resulting ^{22}Ne/^{20}Ne source ratio ~3 times the solar system value of 0.12.

For Mg, the derived ^{25}Mg + ^{26}Mg source fraction of 0.33(+0.09, −0.07) (Fig. 3) corresponds to a (^{25}Mg + ^{26}Mg)/^{24}Mg source ratio that is 1.8(+0.08, −0.05) times the solar system value of 0.27. From a maximum likelihood analysis we find for both ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg that there is less than a 10% probability that the cosmic-ray source ratio is identical to that of the solar system. For (^{25}Mg + ^{26}Mg)/^{24}Mg the corresponding probability is only 5%. For ^{29}Si and ^{30}Si our observations are statistically limited, and the data do not rule out the possibility that these nuclei are also enhanced in the cosmic-ray source.

V. DISCUSSION

Because the masses of the individual isotopes of Ne, Mg, and Si differ by $\leq 10\%$, mass-dependent acceleration effects are unlikely to be significant, and the isotopic anomalies in the derived cosmic-ray source composition more likely reflect the composition of the material from which cosmic rays are accelerated. Garcia-Munoz, Simpson, and Wefel (1979) argued that the interstellar medium (ISM) could not be the dominant component of cosmic-ray source material, because the expected change in the ^{22}Ne/^{20}Ne ratio in the ISM since the birth of the solar system is $\lesssim 50\%$. However, a wide variety of neon components are observed in the solar system (see, e.g., Podosek 1978), and it is conceivable that the solar system neon-A component is not representative of the ISM ~4.5×10^9 years ago. We therefore conclude only that the solar system neon-A and cosmic-ray source compositions are different, independent of their origin.

Several mechanisms of nucleosynthesis are thought to contribute to Ne, Mg, and Si isotope production (see, e.g., Trimble 1975). The major contributions to solar system ^{20}Ne, ^{24,25,26}Mg, and ^{29,30}Si are thought to come from explosive carbon burning, while ^{21,22}Ne production is the result of He burning, and ^{28}Si is due mainly to explosive oxygen burning. Woosley (1979) suggested two factors that might lead to cosmic-ray ^{22}Ne enhancements; we discuss below their implications for the Mg and Si isotopes.

One factor contributing to the ^{22}Ne enhancement might be continuing galactic evolution (see also Maehl *et al.* 1975), since ^{22}Ne and other neutron-rich nuclei are second-generation products of nucleosynthesis. Because the cosmic rays (age ~ 2×10^7 years) are much younger than the solar system, they may reflect contributions from later stars of higher average metallicity. During helium burning, the larger abundance of metals will result in an increased abundance of ^{22}Ne, which in turn is the source of an increased neutron excess η during explosive carbon burning.

The Mg isotopes are particularly sensitive to η, as noted by Silberberg, Shapiro, and Tsao (1975) and by

Cassé (1980). Based on Figure 3 of Pardo, Couch, and Arnett (1974), our ^{25}Mg + ^{26}Mg excess would result from an increase in η of 30 ± 20% over the solar system value of $\eta \approx 2 \times 10^{-3}$. On the other hand, a factor of $\sim$3 increase in η, as suggested by ^{22}Ne, would lead to ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg ratios both >1. It therefore appears unlikely that the Ne and Mg isotope measurements can be explained in a consistent manner in terms of galactic evolution effects alone.

Since ^{20}Ne and ^{22}Ne are produced in different burning processes in different zones of a massive star, Woosley (1979) suggested that a second contributing factor to a nonsolar ^{22}Ne/^{20}Ne ratio might be a variation in the relative contribution of these zones, as might be expected if the cosmic rays and the solar system come from stars of different average mass (see, e.g., Hainebach, Norman, and Schramm 1976). We note from Couch, Schmiedekamp, and Arnett (1974), and from Lamb *et al.* (1977), that in stars with $\sim$8 to $\sim$50 $M_\odot$, ^{22}Ne may provide a source of neutrons for a helium-burning *s*-process with significant yields of ^{25}Mg, ^{26}Mg, and other nuclei including, e.g., ^{58}Fe. A mixture of such helium-burning products with typical carbon-burning yields of ^{20}Ne and ^{24,25,26}Mg (and/or with additional material of solar-system composition) could produce the cosmic-ray source Ne and Mg composition (Table 1) if the helium-burning yield of ^{25}Mg + ^{26}Mg did not exceed that of ^{22}Ne, a constraint that places limits on the average mass of the stars involved. We conclude that an enrichment of helium burning products in cosmic rays can enhance both ^{22}Ne/^{20}Ne and (^{25}Mg + ^{26}Mg)/^{24}Mg, as observed, without significantly affecting ^{21}Ne or the silicon isotopes. Observations of other *s*-process nuclei in cosmic rays (see, e.g., Wefel, Schramm, and Blake 1977) might test this possibility.

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REFERENCES

Althouse, W. E., Cummings, A. C., Garrard, T. L., Mewaldt, R. A., Stone, E. C., and Vogt, R. E. 1978, *Geoscience Electronics*, **16**, 204.

Cameron, A. G. W. 1973, *Space Sci. Rev.*, **15**, 121.

Cassé, M. 1980, *Ap. J.*, submitted.

Couch, R. G., Schmiedekamp, A. B., and Arnett, W. D. 1974, *Ap. J.*, **190**, 95.

Dietrich, W. F., and Simpson, J. A. 1979, *Ap. J.* (*Letters*), **231**, L91.

Dwyer, R. 1978, *Ap. J.*, **224**, 691.

Fisher, A. J., Hagen, F. A., Maehl, R. C., Ormes, J. F., and Arens, J. F. 1976, *Ap. J.*, **205**, 938.

Fisk, L. A. 1971, *J. Geophys. Res.*, **76**, 221.

Garcia-Munoz, M., Mason, G. M., and Simpson, J. A. 1977*a*, *Proc. 15th Internat. Cosmic Ray Conf.* (Plovdiv: Bulgarian Academy of Sciences), **1**, 301.

———. 1977*b*, *Proc. 15th Internat. Cosmic Ray Conf.* (Plovdiv: Bulgarian Academy of Sciences), **1**, 224.

Garcia-Munoz, M., Mason, G. M., Simpson, J. A., and Wefel, J. P. 1977, *Proc. 15th Internat. Cosmic Ray Conf.* (Plovdiv: Bulgarian Academy of Sciences), **1**, 230.

Garcia-Munoz, M., Simpson, J. A., and Wefel, J. P. 1979, *Ap. J.* (*Letters*), **232**, L95.

Geiss, J. 1973, *13th Internat. Cosmic Ray Conf.* (Denver: University of Denver), **5**, 3375.

Gleeson, L. J., and Axford, W. E. 1968, *Ap. J.*, **154**, 1011.

Greiner, D. E., Wiedenbeck, M. E., Bieser, F. S., Crawford, H. J., Heckman, H. H., and Lindstrom, P. J. 1979, LBL-8921, to be presented at *16th Internat. Cosmic Ray Conf.*, Kyoto. Paper OG 7-10.

Hainebach, K. L., Norman, E. B., and Schramm, D. N. 1976, *Ap. J.*, **203**, 245.

Lamb, S. A., Howard, W. M., Truran, J. W., and Iben, I., Jr. 1977, *Ap. J.*, **217**, 213.

Lezniak, J. A., and Webber, W. R. 1978, *Ap. J.*, **223**, 676.

Maehl, R. C., Fisher, A. J., Hagen, F. A., and Ormes, J. F. 1975, *Ap. J.* (*Letters*), **202**, L119.

Mewaldt, R. A., Spalding, J. D., Stone, E. C., and Vogt, R. E. 1979, *Ap. J.* (*Letters*), **231**, L97.

Pardo, R. C., Couch, R. G., and Arnett, W. D. 1974, *Ap. J.*, **191**, 711.

Podosek, F. A. 1978, *Ann. Rev. Astr. Ap.*, **16**, 293.

Prezler, A. M., Kish, J. C., Lezniak, J. A., Simpson, G., and Webber, W. R. 1975, *14th Internat. Cosmic Ray Conf.* (Munich: Max-Planck-Institut für Extraterrestrische Physik), **12**, 4096.

Silberberg, R., Shapiro, M. M., and Tsao, C. H. 1975, *14th Internat. Cosmic Ray Conf.* (Munich: Max Planck-Institut für Extraterrestrische Physik), **2**, 451.

Silberberg, R., Tsao, C. H., and Shapiro, M. M. 1976, in *Spallation Nuclear Reactions and their Applications*, ed. B. S. P. Shen and M. Merker (Dordrecht: Reidel), p. 49.

Simpson, G. A., Kish, J. C., Lezniak, J. A., and Webber, W. R. 1977, *15th Internat. Cosmic Ray Conf.* (Plovdiv: Bulgarian Academy of Sciences), **1**, 347.

Stone, E. C., and Wiedenbeck, M. E. 1979, *Ap. J.*, **231**, 606.

Trimble, V. 1975, *Rev. Mod. Phys.*, **47**, 877.

Wefel, J. P., Schramm, D. N., and Blake, J. B. 1977, *Ap. Space Sci.*, **49**, 47.

Woosley, S. E. 1979, personal communication.

Note added in proof.—In recent calculations of explosive neon-burning, Woosley and Weaver (submitted to *Ap. J.*, 1979) find that an initial stellar metallicity 2.5 times that of the solar system results in Ne, Mg, and Si isotopic abundances consistent with the cosmic ray source abundances presented here.

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