Distributed Acceleration of Cosmic Rays

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It is proposed that the acceleration of cosmic rays is distributed over their propagation through interstellar space. Thus after most nuclear fragmentation reactions in the interstellar medium, cosmic rays gain about a factor of 5 in energy. This hypothesis resolves several discrepancies in composition at different energies. The present results suggest that after the principal acceleration and during their galactic confinement, cosmic rays are further accelerated by the weak shocks of widely distributed old supernova remnants.

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Cosmic rays consist mainly of relativistic protons and heavier nuclei. About half of the heavy nuclei leaving the cosmic-ray sources collide during propagation through the interstellar gas, building up many secondary nuclides. A detailed review of cosmic-ray propagation has been given by Shapiro and Silberberg.[1] Studies of cosmic-ray composition—and calculations of *source* abundances—assume that most nuclear fragmentation in the interstellar medium takes place after acceleration. With this assumption, however, puzzling discrepancies in isotopic and elemental composition remain. We noted that the calculated abundance ratio $(61 \leq Z \leq 75)/(76 \leq Z \leq 83)$ was brought into agreement with observations at 5 GeV/nucleon by assuming that cosmic rays are accelerated (with a fivefold increase in energy) after most fragmentation has taken place. We then deduced several other abundance ratios under this hypothesis. The hypothesis appears to be reinforced by the resolution of many other discrepancies listed below: (1) raising the anomalously low estimate of N at cosmic-ray sources, so that it fits the relative solar system abundances; (2) reducing the high estimates of source abundance for F, Na, and Al obtained from cosmic-ray propagation calculations at low energies (near 150 MeV/nucleon) so that they agree with the values deduced at high energies and with the general abundance of elements in nature; (3) reducing the calculated abundances of the electron-capture isotopes, e.g., ^{37}Ar, ^{49}V, and ^{51}Cr, so as to fit the data near 600 MeV/nucleon; and (4) reducing the calculated source abundances of the subiron elements Mn and Cr at low energies (about 250 MeV/nucleon), so that they agree with the general abundance of elements in nature. When these effects are considered together, they provide strong evidence for distributed acceleration. Further tests for verification are suggested in this paper.

The first two effects above are related to the energy dependence of (p,pn) reactions. The cross sections for (p,pn) reactions are large at all energies; hence their contribution to secondary cosmic rays is important. These cross sections are larger still at low energies, having a peak near 40 MeV, ~3 times as large as the high-energy value (see Fig. 12 of Ref. 1). Hence, if cosmic rays are accelerated by a factor of 5 after most fragmentation, and suffer adiabatic losses of ~200 MeV/nucleon in the solar system, the products of (p,pn) reactions should appear anomalously enhanced for $E_0 < 400$ MeV/nucleon. Here E_0 is the energy per nucleon when *observed*; E_f is the energy per nucleon at the time of fragmentation. [The energies of the fragmenting nuclei would be $E_f < 120$ MeV/nucleon, since $E_f = (E_0 + 200)/5$ MeV/nucleon.]

The source abundance of nitrogen relative to oxygen is given roughly by the relation[2]

$$(^{14}\mathrm{N/O})_{\mathrm{source}} = (^{14}\mathrm{N/O})_{\mathrm{obs}} - (\sigma_{14}/\sigma_{15})(^{15}\mathrm{N/O})_{\mathrm{obs}}. \quad (1)$$

Isotopic abundance measurements of nitrogen at

TABLE I. Comparison of calculated source abundances near $E_0 = 150$ MeV/nucleon with solar system abundances.

Element	Calculated Standard	Calculated This paper	Solar system
F/Mg	0.04 ± 0.01	0.02 ± 0.01	0.001
Na/Mg	0.11 ± 0.03	0.06 ± 0.03	0.057
Al/Mg	0.14 ± 0.03	0.07 ± 0.03	0.080

TABLE II. Electron-capture nuclides, $600 < E_0$ (MeV/nucleon) < 800.

Nuclides	Events[a]	Expected No decay[a]	Expected This calculation
^{37}Ar	<10	25 ± 10	12 ± 10
^{49}V	36 ± 11	56 ± 20	28 ± 20
^{51}Cr	23 ± 14	53 ± 20	26 ± 20

[a]Ref. 13.

energies $50 < E_0 < 150$ MeV/nucleon[3-5] yield $(^{14}\mathrm{N/O})_{\mathrm{obs}} = 0.13 \pm 0.01$ and $(^{15}\mathrm{N/O})_{\mathrm{obs}} = 0.16 \pm 0.01$. Prior to adiabatic deceleration in the heliosphere, the energy was 250–350 MeV/nucleon. The ratio of total production cross sections $(\sigma_{14}/\sigma_{15})$ for ^{14}N and ^{15}N from ^{16}O is derived by scaling results for the high-energy production cross sections to the boron production cross sections of Fontes.[6] If a fivefold gain in energy occurred after most of the propagation, the cross sections in the energy range $50 < E_f < 70$ MeV/nucleon are appropriate; thus $(\sigma_{14}/\sigma_{15}) = 0.41$ and $(^{14}\mathrm{N/O})_{\mathrm{source}} = 0.064 \pm 0.01$. (The standard calculation yields a value lower by 1.5 standard deviations.) This is consistent with the mean value of 0.08 ± 0.01 of Lezniak and Webber[7] and Perron *et al.*,[8] based on elemental abundances measured at energies $E_0 > 1$ GeV/nucleon. It is also consistent with Meyer's[9] "local galactic" abundance estimate of 0.10 ± 0.04.

The (p,pn) and also the $(p,2p)$ reactions of the abundant nuclides ^{20}Ne, ^{24}Mg, and ^{28}Si after decay yield ^{19}F, ^{23}Na, and ^{27}Al. The abundances of the latter have been measured by Dwyer *et al.*[10] near energies E_0 of 150 MeV/nucleon (after adiabatic

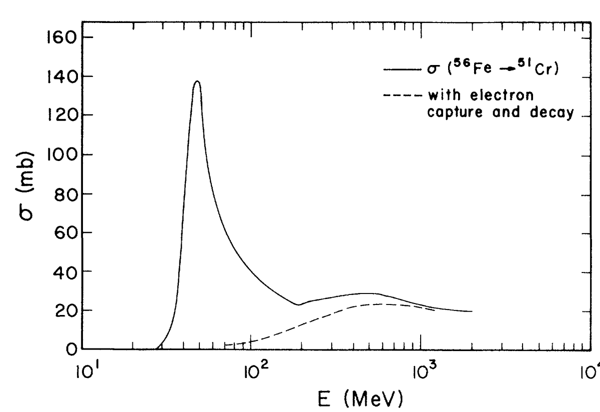

FIG. 1. Illustration of (i) the large cross sections of Fe near and below 100 MeV for small values of target-product mass difference, and (ii) effect of correction for electron attachment and decay in interstellar space.

deceleration by ~200 MeV/nucleon). With use of the appropriate low-energy ($E_f \sim 70$ MeV/nucleon) cross sections, which are 1.5 to 2.0 times higher, the secondary contributions to F, Na and Al are enhanced; thus the residual source components (the observed abundance minus the secondary component) are 40%–50% smaller, and in better agreement with the high-energy values[7,8] and the general abundance estimates of Cameron[11] (see Table I).

The nuclides with mass numbers $A = 35$ to 55, that can decay by electron capture, e.g., ^{49}V, have a probability of ~50% for electron attachment and capture at 200 MeV/nucleon.[12] (At 100 MeV/nucleon, the probability is >75%). Figure 1 shows the cross section $\sigma(^{56}\mathrm{Fe} \to {}^{51}\mathrm{Cr})$ as a function of energy, and the "effective cross section" for ^{51}Cr that survives against decay due to electron attachment. After acceleration to 1000 MeV/nucleon and adiabatic losses of 200 MeV/nucleon, the particles at $E_f = 200$ MeV/nucleon (at which energy half the nuclides with mass numbers $A = 35$ to 55 decay) are observed at $E_0 = 800$ MeV/nucleon. Table II shows the measured and "expected" abundances near 600 to 800 MeV/nucleon of Webber.[13] With the fivefold energy gain proposed here, the recalculated expected values are lower by a factor of 2, and agree well with the measured values. The abundances of remaining electron-capture isotopes ^{41}Ca, ^{55}Fe, and ^{57}Co have not yet been measured because of difficulties of identification near very abundant neighboring isotopes. We *predict* a similar reduction in these nuclides below $E_0 = 800$ MeV/nucleon. This hypothesis can also be tested by measuring the ratios ^{51}Cr/Cr and ^{49}V/V as a function of energy. If the hypothesis is correct, both ratios decrease with decreasing energy below 800 MeV/nucleon; otherwise they are nearly constant.

The measured ratio $(61 \leq Z \leq 75)/(76 < Z \leq 83)$ with a mean energy E_0 near 5 GeV/nucleon[2,14,15] is lower by a factor of about 3 than the value obtained in propagation calculations. Measurements of Kaufman and Steinberg[16] show that the spallation cross sections of ^{197}Au (in the interval 76 $\leq Z \leq 83$) are ~2.5 times larger near 1 GeV/nucleon. Table III compares the experimental relative abundances of the elements in the charge intervals 63 to 70, 71 to 76, and 77 to 83 at ~5 GeV/nucleon with our calculations based on the new cross-section calculations of Tsao, Silberberg, and Letaw[17] under the alternative assumptions (a) no acceleration and (b) energy gain by a factor of 5. With assumption (b), the fit to the experimental data is improved considerably. (A leakage path length of 6 g/cm^2 and 7% helium in the intersetllar medium were assumed.)

The calculated source abundances[10] of Cr and Mn at $E_0 = 250$ MeV/nucleon are about 4 ± 2 times greater than expected on the basis of the general abundances.[10] Since the spallation cross sections of Fe for $\Delta A \leq 6$ increase appreciably[18] below 150 MeV/nucleon as shown in Fig. 1, the distributed acceleration model ($E_f \sim 100$ MeV/nucleon) implies increased secondary production of Cr and Mn and reduces the estimated source component. Cross-section uncertainties and the dominance of secondaries prevent an exact estimate of the latter.

An additional test of distributed acceleration was carried out. One may wonder: Are the calculated abundances of Cl, Ar, and K near $E_f \sim 100$ MeV/nucleon sufficiently high to fit the data[10] near $E_0 = 250$ MeV/nucleon. Their secondary yields from Fe at these energies are small. The experimental ratio (Cl, Ar, K)/Fe = 0.24 ± 0.02 is in reasonable agreement with our calculated ratio 0.20 ± 0.03. The tertiary contribution from Fe via $21 \leq Z \leq 25$, and the large low-energy yields from Ca with $\Delta A < 5$ thus produce a sufficient number of Cl, Ar, and K nuclei.

The statistical errors of the cross sections have been included in Tables I–III; the major part of the error quoted is due to this source.

TABLE III. The abundances of ultraheavy elements at 5 GeV/nucleon (Fe = 100).

Elements	Experiment	Calculated Standard	Calculated This paper
Secondaries			
$63 \leq Z \leq 70$	5.5 ± 1	2.9 ± 1	4.0 ± 1
$71 \leq Z \leq 76$	2.6 ± 0.5	1.5 ± 0.7	2.2 ± 1
Primaries			
$77 \leq Z \leq 83$	3.5 ± 1	3.3	3.4

While one could claim that there may be systematic effects in a class of cross sections, e.g., (p, pn) reactions, our conclusions are based on several independent classes of cross sections.

Each of the arguments for distributed acceleration presented above indicates roughly a one standard deviation improvement in prediction of observed or source abundances. These improvements (eleven in total, in several independent classes) taken together are unlikely to be attributable to chance. They provide strong evidence for the proposition that cosmic rays undergo accelerations which are distributed over the propagation through interstellar space.

The production of antiprotons is not explained by the hypothesis of distributed acceleration, since the cross section increases with energy. Special assumptions for antiprotons must be invoked. However, the standard propagation model also requires special assumptions, e.g., a source of cosmic-ray protons imbedded in dense clouds.

An energy gain of cosmic rays subsequent to nuclear breakup reactions has other important ramifications. From the surviving fraction of the long-lived radioactive nuclide ^{10}Be ($\tau_{1/2} = 1.6 \times 10^6$ yr), one calculates the "age" or confinement time T of cosmic rays in the galaxy. The mean value of T, obtained by Wiedenbeck and Greiner[19] and Garcia-Munoz, Simpson, and Wefel[20] is $\sim 10^7$ yr. At low energies (150 MeV/nucleon) the ratio of the cross sections $\sigma(^{12}\mathrm{C} \to {}^{10}\mathrm{Be})/\sigma(^{12}\mathrm{C} \to {}^{7}\mathrm{Be})$ is $\frac{1}{5}$ of that at 2 GeV.[21,22] With the lower-energy cross sections, less ^{10}Be is produced, and hence less decay is required to reproduce the observed value; less decay implies a shorter galactic confinement time. The energy dependence of cross sections and the energy gain by a factor of 5 imply that the estimated "age" is cut in half.

The "late" energy boost could be understood in the general shock-wave framework of Axford, Leer, and Scadron,[23] and Blandford and Ostriker.[24] The principal acceleration of cosmic rays is probably effected by strong shock waves of a young supernova remnant. Montmerle[25] has proposed the origin of cosmic rays in OB stellar associations with interstellar clouds where these massive short-lived stars turn into supernovae. *During the subsequent galactic confinement time, cosmic rays are much more likely to encounter the widely distributed dissipated shocks of old supernova remnants than the small regions of the young remnants.* Encountering these weak shocks, acceleration occurs without distortion of the secondary/primary ratios, as shown by Axford.[26]

Thus our conclusions suggest a model of the interstellar medium characterized by widely distributed and somewhat dissipated supernova shocks. Detailed investigation of the nature of these shocks is the province of plasma physics. Further measurements of nuclear cross sections at low energies are needed to make more accurate abundance predictions. It is of considerable importance that propagation calculations of all groups doing cosmic-ray research are brought into question by this work. If the cross sections at an inappropriate energy are being used, many of the conclusions about origin, propagation, and acceleration of cosmic rays are spurious.

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