Reports

Cosmic Ray Sources: Evidence for Two Acceleration Mechanisms

Abstract. *The difference between the energy spectra of iron and other cosmic rays is interpreted in terms of two source mechanisms. One mechanism, possibly acceleration at neutron star surfaces, produces the iron, and another is responsible for the rest of the primary nuclei. Within this model, observations of high-energy cosmic rays could determine whether secondary nuclei are produced in the sources or in the interstellar medium.*

Recent experimental data on the composition of the nuclear cosmic radiation (*1–4*) in the energy range 1 to 100 billion electron volts (Gev) per nucleon has led to questions about the previously accepted notion that all cosmic ray spectra are the same at high energies. While there are detailed differences, the data all indicate that the ratios of C, N, and O nuclei to Fe nuclei and of secondary cosmic rays to primary cosmic rays decrease with increasing energy. (Primary nuclei are directly accelerated in the cosmic ray sources, and secondary nuclei are produced predominantly by spallation reaction of the primaries with matter between the sources and the earth.) In this report we explore the implications on source composition and cosmic ray propagation of data obtained with the balloon-borne ionization spectrometer from Goddard Space Flight Center, Greenbelt, Maryland. The details of the experimental data will be published elsewhere (*5*); the main results are summarized in Fig. 1. Here we wish to show that these data imply that iron nuclei could have a different origin than the rest of the primary cosmic rays.

Spectra of protons, alpha particles, carbon, oxygen, nuclei of atomic number Z between 10 and 14, and iron group nuclei are shown in Fig. 1. In limited energy ranges these spectra can be represented by power laws of the form $\varphi \propto E^{-\gamma}$, where φ is the differential flux, E is the energy, and γ is the spectral index. The heavy solid and heavy dashed lines in Fig. 1 represent maximum-likelihood fits to the medium (C,N,O) and Fe groups in the energy range 3 to 50 Gev per nucleon. The spectral indexes of these groups are 2.64 ± 0.04 and 2.12 ± 0.13, respectively (*2*). The power law that fits the spectrum of medium (M) nuclei also fits the group with Z between 10 and 14; in addition the same power law seems to fit the spectra of protons and alpha particles in the range 5 to 50 Gev per nucleon, although at higher energies the spectra appear steeper. Thus, within the experimental uncertainties, all primary nuclei with $Z \leqslant 14$ have similar spectra in the same range of energy per nucleon. Note, however, the large difference of 0.52 ± 0.15 between the spectral index of the iron group and that of primary nuclei lighter than iron (*6*).

In Fig. 2 the ratio of the secondary nuclei Li, Be, and B (the light or L nuclei) to their immediate progenitors C, N, and O is plotted as a function of energy per nucleon. The spectral index of the L group is 2.78 ± 0.07 (*2*). The difference in spectral index between the L and M groups is 0.14 ± 0.08 from about 1 to 20 Gev per nucleon, in agreement with a similar difference reported by Smith *et al.* (*4*). Both measurements indicate that secondary nuclei have steeper spectra than their primary progenitors. However, the difference between the spectrum of iron and the spectrum of the other primary nuclei is significantly larger than the difference between the spectra of the primary and secondary nuclei. A similar conclusion may be obtained from the data for iron and its secondaries (*2, 3*), although with less compelling statistical significance.

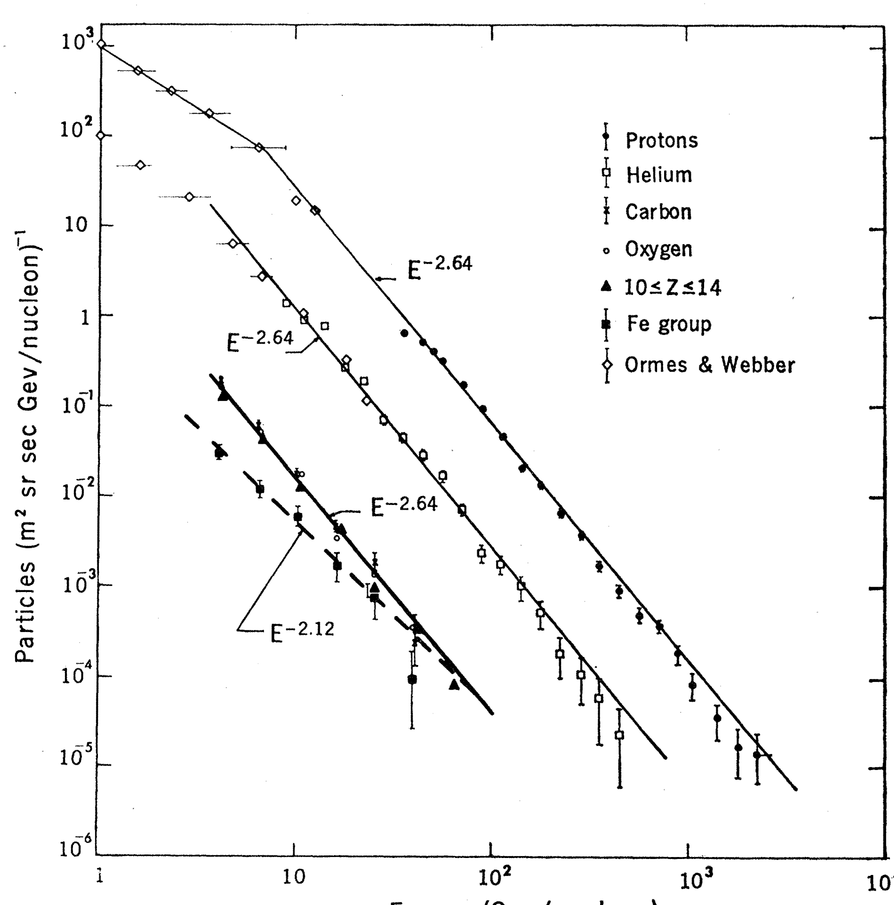

Fig. 1. Intensities of primary cosmic rays from protons to iron. The data are from (*5*) and from Ormes and Webber (*18*).

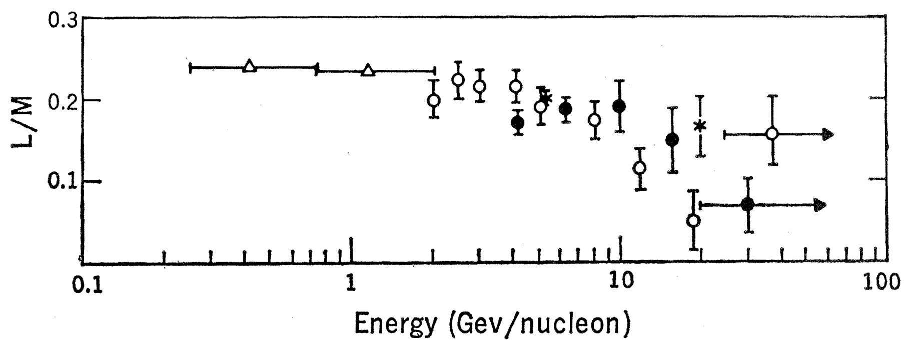

Fig. 2. Ratio of light (L) to medium (M) nuclei. The sources of the data are: open circles (*4*), closed circles (*5*), triangles (*10*), and asterisks (*3*).

The difference in spectral index of primary and secondary nuclei has been interpreted in terms of energy-dependent propagation of cosmic rays in the interstellar medium (*1, 3, 7*). In a steady-state model with exponential distribution of path length [for example, see (*8*)], the ratio of the fluxes of L and M nuclei may be calculated from

$$\frac{\varphi_L}{\varphi_M} = \frac{XX_L}{X_{ML}(X + X_L)} \times \left[1 + \frac{X_{ML}\varphi_{LH}}{X_{LHL}\varphi_M} + \frac{X_{ML}\varphi_{Fe}}{X_{FeL}\varphi_M}\right] \quad (1)$$

where φ is a cosmic ray flux at the earth, and the subscripts LH and Fe denote nuclei with Z between 10 and 14 and Z between 23 and 28, respectively. The quantity X is the e-folding path length of the exponential distribution (or the mean escape path length of cosmic rays from the galaxy); X_L is the nuclear destruction path length of L nuclei; and X_{ML}, X_{LHL}, and X_{FeL} are the fragmentation path lengths of M, LH, and Fe nuclei into L nuclei.

Based on cross sections from (*9*), we have $X_L = 13$, $X_{ML} = 19$, $X_{LHL} = 29$, and $X_{FeL} = 33$ g cm^{-2}. We take the observed flux ratios from Figs. 1 and 2 and (*2*) as follows:

$$\varphi_L/\varphi_M = 0.23E^{-0.14 \pm 0.8}$$

$$\varphi_{LH}/\varphi_M = 0.28$$

$$\varphi_{Fe}/\varphi_M = 0.036E^{0.52 \pm 0.15}$$

The path length X, determined by solving Eq. 1, is plotted as a function of energy per nucleon in the lower part of Fig. 3. At 1 Gev, $X = 5$ g cm^{-2}, a value consistent with previous calculations (*8*) of cosmic ray fragmentation. The shaded area represents the uncertainty in X introduced by uncertainties in the spectral indexes of both φ_L/φ_M and φ_{Fe}/φ_M; the error bars represent uncertainties from φ_L/φ_M alone. The uncertainty in φ_{Fe}/φ_M has almost no effect on X below approximately 10 Gev per nucleon, and about a 10 percent effect at 40 Gev per nucleon.

Consider now the ratio of iron to medium nuclei. In the steady-state model, the source ratio $(Fe/M)_s$ may be calculated from

$$(Fe/M)_s = \frac{\varphi_{Fe}}{\varphi_M}\frac{1 + X/X_{Fe}}{1 + X/X_M}(1 - \varphi_{Ms}/\varphi_M)^{-1} \quad (2)$$

where X_M and X_{Fe} are the destruction path lengths of medium and iron nuclei, and φ_{Ms} is the flux of medium nuclei of secondary origin. The ratio φ_{Ms}/φ_M is energy dependent because of the energy dependence of the iron-to-medium ratio. However, because there is relatively little fragmentation of iron into the M group, we shall use the constant value $\varphi_{Ms}/\varphi_M = 0.16$ previously determined (*8*).

The source ratio $(Fe/M)_s$ from Eq. 2 is plotted in the upper part of Fig. 3. As before, the shaded area represents the uncertainty in $(Fe/M)_s$ introduced by uncertainties in both φ_L/φ_M and φ_{Fe}/φ_M, whereas the error bars result from φ_L/φ_M alone.

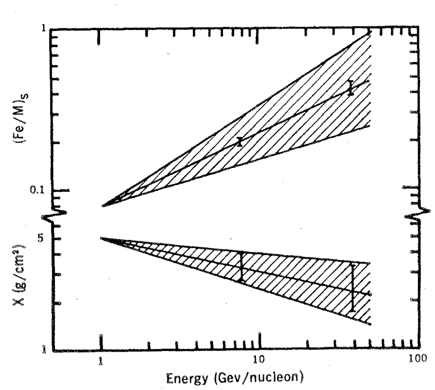

Fig. 3. Source ratio of iron to medium nuclei $(Fe/M)_s$ and escape path length of cosmic rays in the galaxy X. The shaded areas and error bars are discussed in the text.

The source ratio $(Fe/M)_s$ is about 0.08 at 1 Gev per nucleon. This value is in good agreement with ratios previously calculated from energy-independent results: $(Fe/M)_s = 0.11$ (*9*), $(Fe/M)_s \simeq 0.1$ (*8*), $(Fe/M)_s \simeq 0.09$ (*10*). At higher energies, however, $(Fe/M)_s$ exhibits a significant departure from a constant, which cannot be explained by propagation effects alone. That propagation effects have only a small influence on $(Fe/M)_s$ can be seen from the fact that most of the uncertainty in $(Fe/M)_s$ comes from uncertainties in φ_{Fe}/φ_M; the effect of φ_L/φ_M is small.

Evidence against a constant $(Fe/M)_s$ also comes from a comparison of the observed energy-dependent ratio φ_{Fe}/φ_M as given above with the low-energy value of $(Fe/M)_s$. Because more iron nuclei than medium nuclei are broken up during propagation, the iron-to-medium ratio at the source must always exceed the iron-to-medium ratio at the earth. The latter, however, increases with increasing energy and becomes comparable to, or perhaps even exceeds, the source ratio (as determined from data around 1 Gev per nucleon) somewhere around 10 to 20 Gev per nucleon. This fact, coupled with the presence of a finite amount of L nuclei at this energy (*2, 3*), implies that an additional mechanism for iron production is required at high energies.

From these considerations we propose a model in which iron is produced by a different source mechanism than all other primary cosmic rays. A reasonable possibility would be the acceleration of iron nuclei in pulsars since the surfaces of the neutron stars in these objects are believed to consist principally of iron (*11*). Because all primary nuclei except iron appear to have the same spectrum, they are interpreted as having a common origin. They could then be produced at any of the proposed sites of cosmic ray acceleration, such as supernova envelopes (*12*) and supernova remnants (*13*).

Let us now examine some of the consequences and predictions of such a two-component model. The difference in spectral index between L and M nuclei is, within errors, the same as the reported difference (*2*) in index between iron and its fragmentation products. This result would imply that most of the fragmentation takes place in the interstellar medium and not in the sources. However, data on the energy dependence of the ratio $(17 \leqslant Z \leqslant 25)/(\mathrm{Fe} + \mathrm{Ni})$ by Webber *et al.* (*3*) appears to indicate that this ratio decreases with increasing energy above 2 Gev per nucleon much more rapidly than the L/M ratio shown in Fig. 2. If this difference is upheld by future data, we shall be able to conclude that most of the cosmic ray fragmentation takes place in the sources and not in the interstellar medium. We should note, however, that in this case the cosmic rays should sample a sufficiently low average density in the interstellar medium. This could be achieved if cosmic rays preferentially avoid interstellar clouds.

Consider now in Fig. 1 the proton spectrum above 50 Gev and the alpha particle spectrum above 10 Gev per nucleon. The maximum-likelihood method yielded spectral indices of 2.75 ± 0.03 and 2.77 ± 0.05 for protons and alphas, respectively (*14*). As discussed above, however, the medium spectrum with index 2.64 fits both the protons and alphas below 50 Gev per nucleon. Thus, there seems to be evidence for a steepening of the proton and alpha particle spectra. A consequence of our model is a similar steepening in the spectra of all nuclei with $Z \leqslant 14$. This spectral change beyond about 50 Gev per nucleon could be due to propagation effects in the interstellar and interplanetary mediums, or it could be produced in the sources. Observations may differentiate between these two possibilities: the spectrum of iron should steepen above 50 Gev per nucleon if we are observing a propagation effect; it should remain the same as below 50 Gev per nucleon if the steepening is produced in the sources of the nuclei with $Z \leqslant 14$. It should be noted that if iron is accelerated at the surfaces of neutron stars, its spectrum may have a different high-energy cutoff due to photonuclear disintegration (*15*). The cutoff energy, however, depends greatly on the pulsar model, and no firm predictions can be made.

Our final prediction with the present model concerns very very heavy (VVH) nuclei (*16*). Since these nuclei are believed to be produced by neutron capture processes and probably are not present on neutron star surfaces, they should not be generically related to iron nuclei. Their spectrum should therefore differ from the spectrum of iron.

In summary, we find that the increase of the ratio of iron nuclei to medium nuclei with increasing energy cannot be easily explained by propagation effects alone, and it appears to require an additional source or acceleration mechanism for iron at high energies. On the basis of a model in which iron comes from a different source than the rest of the primary cosmic rays, we have made predictions of several observable effects. It is hoped that future high-energy cosmic ray experiments, such as those planned for the high-energy astronomical observatory satellite of the National Aeronautics and Space Administration (*17*), can make these observations.

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References and Notes

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21 December 1972; revised 28 February 1973

Obsidian Hydration Dates Glacial Loading?

Abstract. *Three different groups of hydration rinds have been measured on thin sections of obsidian from Obsidian Cliff, Yellowstone National Park, Wyoming. The average thickness of the thickest (oldest) group of hydration rinds is 16.3 micrometers and can be related to the original emplacement of the flow 176,000 years ago (potassium-argon age). In addition to these original surfaces, most thin sections show cracks and surfaces which have average hydration rind thicknesses of 14.5 and 7.9 micrometers. These later two hydration rinds compare closely in thickness with those on obsidian pebbles in the Bull Lake and Pinedale terminal moraines in the West Yellowstone Basin, which are 14 to 15 and 7 to 8 micrometers thick, respectively. The later cracks are thought to have been formed by glacial loading during the Bull Lake and Pinedale glaciations, when an estimated 800 meters of ice covered the Obsidian Cliff flow.*

The thickness of hydration rinds on the surface of obsidian (volcanic glass of rhyolitic composition) increases with age and has been used for dating obsidian artifacts that were manufactured 200 to 250,000 years ago (*1*). Hydration rinds have also been used to measure the age of rhyolite volcanic flows (*2*).

The hydration-rind dating method is based on the ability of a fresh surface of obsidian to adsorb water from the air or soil, and the ability of this adsorbed water to then slowly diffuse into the body of the obsidian at a rate which is dependent mainly on temperature and somewhat on the composition of the glass, but which is independent of humidity. The diffusion front is sharp and can be recognized by the abrupt change in refractive index at the hydration interface (*3*). A preliminary experimental measurement of the rate of hydration as a function of temperature was published by Friedman *et al.* (*3*). Additional experimental work gives a more precise temperature-rate relation, and shows that the rate of hydration increases as a logarithmic function of temperature (*4*).

From measurements made thus far and also from data on archeological material, the thickness of the hydration rind increases linearly with the square root of time:

$$\text{thickness} = \text{constant}\ (\text{time})^{1/2}$$