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COSMIC RAY SOURCES: EVIDENCE FOR TWO ACCELERATION MECHANISMS

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ABSTRACT

The difference between the 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, high energy observations could determine whether secondary nuclei are produced in the sources or in the interstellar medium.

I

Recent experimental data on the composition of the nuclear cosmic radiation (1,2,3,4) in the 1 to 100 GeV/nucleon region has raised questions on the previously accepted notions that all cosmic ray spectra are the same at high energies. These data indicate that the ratios of both medium-to-iron nuclei and secondary-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 reactions of the primaries with matter between the sources and earth). In this paper we wish to explore the implications on source composition and cosmic ray propagation of data obtained from a balloon-borne ionization spectrometer (5). We will show that this data implies that iron nuclei have a different origin than the rest of the primary cosmic rays.

Spectra of protons, alpha particles, carbon, oxygen, $10 \le Z \le 14$, and iron group nuclei are shown in Figure 1. In limited energy ranges these spectra can be represented by power laws $\varphi \propto E^{-\gamma}$, where γ is the spectral index. The heavy solid and heavy dashed lines represent maximum likelihood fits to the medium (C,N,O) and Fe groups in the 3 to 50 GeV/nucleon region. The differential spectral indices of these groups are 2.64 ± 0.04 and 2.12 ± 0.13 respectively (2). The power law fit to the spectrum of medium (M) nuclei also fits the $10 \le Z \le 14$ group; in addition the same power law fits the proton and alpha particle spectra in the 5 to 50 GeV/nucleon region, although at higher energies the spectra appear somewhat steeper. Thus, within the experimental uncertainties, all primary nuclei with $Z \leq 14$ have similar spectra in the same energy per nucleon region. 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.

In Figure 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/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 primary and secondary nuclei. A similar conclusion may be obtained from iron and its secondaries (2) although with less compelling statistical significance.

The difference in spectral index of primary and secondary nuclei can be best interpreted in terms of energy dependent propagation of cosmic rays in the interstellar medium (1, 6). In a steady state model with exponential distribution of path length (e.g. Ref. 7), the ratio of the fluxes of L nuclei to M nuclei may be calculated from

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

where φ is a cosmic ray flux at earth, and the subscripts LH and Fe denote nuclei with $(10 \leq Z \leq 14)$ and $(25 \leq Z)$, respectively (L and M are defined above). 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 Ref. 8, we have that $X_L = 13$ g cm^{-2}, $X_{ML} = 19$ g cm^{-2}, $X_{LHL} = 29$ g cm^{-2} and $X_{FeL} = 33$ g cm^{-2}. We take the observed flux ratios from Figures 1 and 2 and Ref. 2 as follows: $\varphi_L/\varphi_M = 0.23E^{-0.14\pm0.08}$, $\varphi_{LH}/\varphi_M = 0.28$ and $\varphi_{Fe}/\varphi_M = 0.036E^{0.52\pm0.15}$. The path length X as determined by solving equation (1) is plotted as a function of energy/nucleon in the lower part of Figure 3. At 1 GeV, X = 5 g cm^{-2}, a value consistent with previous calculations (7) of cosmic ray fragmentation. The shaded area represents the uncertainty in X introduced by uncertainties in the spectral indices 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 ~ 10 GeV/nucleon and about a 10% effect at 40 GeV.

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

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

where X_M and X_{Fe} are the destruction path lengths of medium and iron nuclei and φ_{M_s} is the flux of medium nuclei of secondary origin. The ratio φ_{M_s}/φ_M is energy dependent because of the energy dependence of the iron-to-medium ratio. However, because of the relatively small fragmentation of iron into the M group, we shall use the constant value $\varphi_{M_s}/\varphi_M = 0.16$ previously determined (7).

The iron-to-medium source ratio from equation (2) is plotted in the upper part of Figure 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.

The source ratio $(Fe/M)_s$ is about 0.08 at 1 GeV/nucleon. This value is in good agreement with ratios previously calculated from energy independent studies: $(Fe/M)_s = 0.11$ (8), $(Fe/M)_s \simeq 0.1$ (7), $(Fe/M)_s \simeq 0.09$ (9). 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.

Straightforward evidence against a constant iron-to-medium source ratio also comes from the comparison of the observed energy dependent ratio $\varphi_{Fe}/\varphi_M \simeq 0.036E^{0.52\pm0.15}$ with the low energy value of $(Fe/M)_s$. Because more iron nuclei are broken up during propagation than medium nuclei, the iron-to-medium ratio at the source must always exceed the iron-to-medium ratio at earth. The latter, however, increases with increasing energy and becomes greater than 0.1 somewhere between 5 and 15 GeV/nucleon. This fact clearly requires an additional mechanism for iron production at higher energies.

From these considerations we conclude that 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 surface of the neutron stars in these objects are believed to consist principally of iron (10). 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 (11) and supernova remnants (12).

Let us now examine the consequences and predictions of such a two component model. The differences 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 $(17 \leq Z \leq 25)/(Fe + Ni)$ ratio by Webber et al. (4) appears to indicate that this ratio decreases with increasing energy above 2 GeV/nucleon much more rapidly than the L/M ratio shown in Figure 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 Figure 1 the proton spectrum above 50 GeV and the alpha particle spectrum above 10 GeV/nucleon. The maximum likelihood method yields spectral indices of 2.75 ± 0.03 and 2.77 ± 0.05 for protons and alphas, respectively (13). As discussed above, however, the medium spectrum with index 2.64 fits both the protons and alphas below 50 GeV/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 $Z \leq 14$. This spectral change beyond about 50 GeV/nucleon could either be due to propagation effects in the interstellar and interplanetary media, or it could be produced in the sources. Observations may differentiate between these two possibilities: the spectrum of iron should steepen above 50 GeV/nucleon if we are observing a propagation effect; it should remain the same as below 50 GeV/nucleon if the steepening is produced in the sources of the $Z \leq 14$ nuclei. It should be noted, however, that if iron is accelerated at the surfaces of neutron stars, its spectrum may have a different high-energy cutoff due to photonuclear disintegration (14). The cutoff energy, however, depends greatly on the pulsar model, and no firm predictions can be made.

One final prediction of the present model concerns VVH nuclei (15). 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-to-medium nuclei with increasing energy cannot be explained by propagation effects alone, and it appears to require an additional source or acceleration mechanism for iron at high energies. Based on a model in which iron comes from a different source than the rest of 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 NASA's High Energy Astronomical Observatory Satellite (17), can make these observations.

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FIGURE CAPTIONS

1. Intensities of primary cosmic rays from protons to iron. The data are taken from the Ref. 5 and from Ormes and Webber(16).

2. The ratio of light to medium nuclei. The data are taken from the references indicated in the Figure.

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

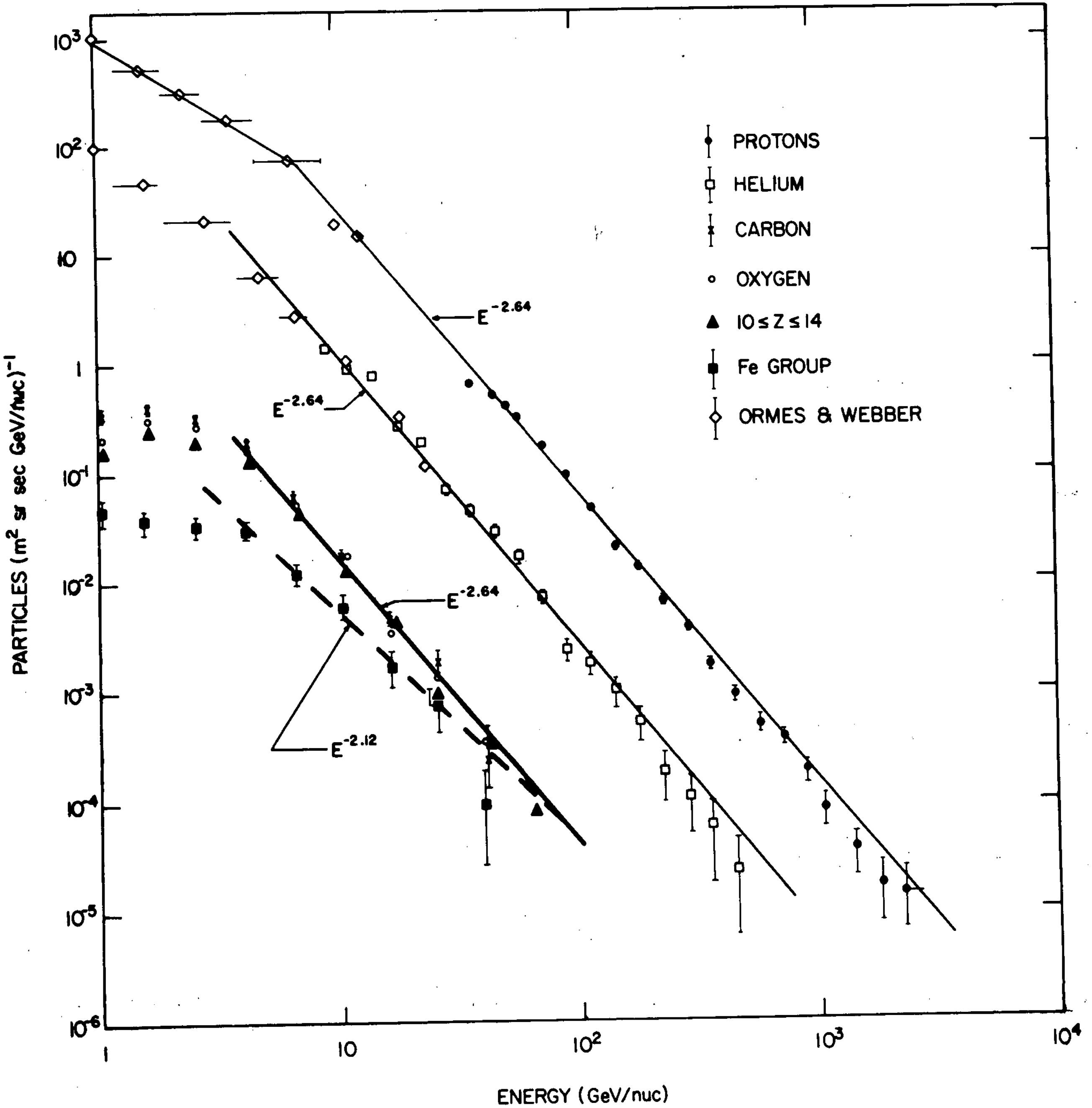
PROTONS
HELIUM
CARBON
OXYGEN
$10 \leq Z \leq 14$
Fe GROUP
ORMES & WEBBER
$E^{-2.64}$
$E^{-2.64}$
$E^{-2.64}$
$E^{-2.12}$
PARTICLES $(m^2\ sr\ sec\ GeV/nuc)^{-1}$
ENERGY (GeV/nuc)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
10
10^2
10^3
10^4

FIGURE 1

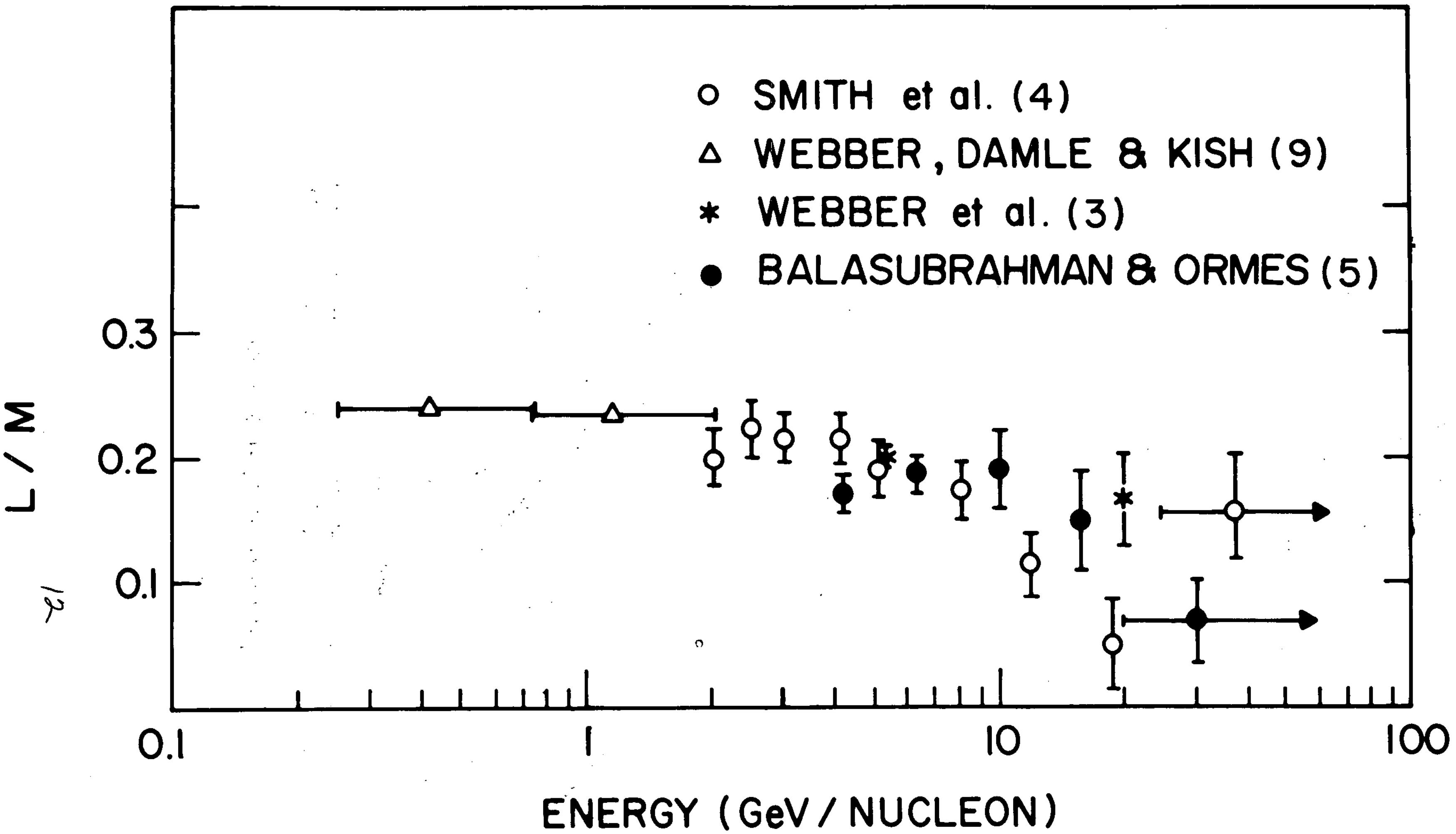
○ SMITH et al. (4)
△ WEBBER, DAMLE & KISH (9)
* WEBBER et al. (3)
● BALASUBRAHMAN & ORMES (5)
L / M
0.3
0.2
0.1
0.1
1
10
100
ENERGY (GeV / NUCLEON)

FIGURE 2

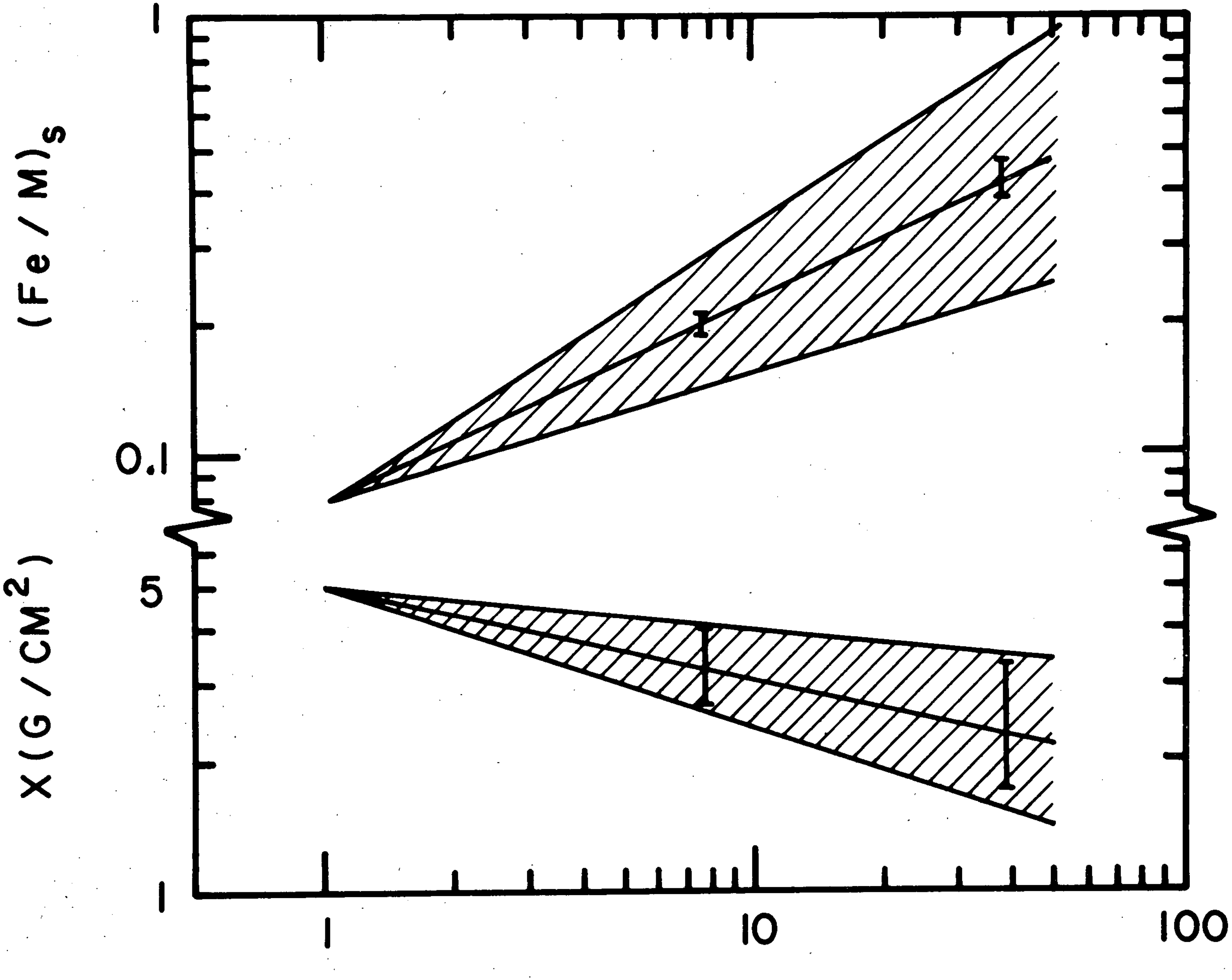

FIGURE 3

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