COSMIC RAY NUCLEI OF ENERGY > 50 GeV/NUC

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ABSTRACT

Preliminary results from the High Energy Gas Cherenkov Spectrometer indicate that the sub-iron to iron ratio increases beyond 100 GeV/nucleon. This surprising finding is examined in light of various models for the origin and propagation of galactic cosmic rays.

1. Introduction. The study of the composition of cosmic radiation and its energy distribution has resulted in the development of several models of cosmic ray propagation and information about sources and acceleration phenomena (Cesarsky, 1980) [1]. The results from several balloon experiments and the good statistics data from the HEAO-C measurement (Englemann et al., 1985) [2] indicate that the matter traversed by cosmic rays decreases with energy. In the energy range 1-25 GeV/nuc, this dependence of matter traversed by cosmic rays is expressed as $(\text{rigidity})^{-0.6}$. This trend, if continued beyond 50 GeV/nuc, would result in matter traversed decreasing below 1 g/cm^2. As the amount of matter becomes small, the effects of nuclear interaction in the Interstellar Medium (ISM) become difficult to detect if the nuclear mean free path (λ) in the ISM is much larger than 1 g/cm^2. For Fe nuclei λ = 2.8 g/cm^2 and so relatively Fe becomes a more suitable nucleus to study compared to C, O. The widely differing consequences predicted by the leaky box, nested leaky box, and the closed galaxy models could be tested by studying the relative amounts of primary Fe nuclei and the secondaries from the breakup process.

In addition to these theoretical models, the results from the experiments on the detection of antiprotons (Golden et al., 1979, [3] Bogomolov et al., 1979, [4] Buffington et al., 1981) [5] suggest that the matter traversed by cosmic ray protons may not be consistent with cosmic ray propagation models derived from the study of heavy nuclei. In this, we discuss some of the suggestive trends seen in the preliminary data of the High Energy Gas Cherenkov Spectrometer (HEGCS) and see what we can learn about the conflicting requirement of these phenomena. Details regarding the HEGCS experiment and data analysis are reported in the proceedings of the Conference (paper OG 4.1-11, Streitmatter et al., 1985) [6].

2. Data in Fe and Sub-Fe Region. In the lower energy region up to 25 GeV/nuc, the HEAO-C (Englemann et al., 1985) [2] with its excellent charge resolution and statistics gives a reliable data base. Beyond 25 GeV/nuc, several balloon experiments (Simon et al., 1980, [7] and references therein, and Streitmatter et al., 1985) [6] provide data. The very low flux of the particles to be detected is the most serious problem for statistical reliability. Beyond a few hundred GeV/nuc, the situation is even more murky. JACEE's (Burnett et al., 1983) [8] finding that the highest energy particle was not an Fe but a Ca and the absence of Fe nuclei up to a total energy of 10^{14} eV is in contrast with

the delayed particle EAS experiment of the Maryland group (Goodman et al., 1982) [9]. The Maryland group concludes that their results are consistent with a Fe spectrum with a power law exponent $-2.39 \pm .09$. It is to be remembered, however, that EAS experiments have no charge resolution to discriminate between Fe primaries and secondaries of Fe.

In Figure (1) we show the preliminary results from HEGCS in the Fe and sub Fe group. The secondaries of Fe seem to cluster at either the low or high Cherenkov signal, with a paucity of points in between. Fe, however, seems to be distributed more uniformly throughout, with the number of points tapering off at the high signal limit.

Maximum likelihood estimates of the power law exponent for iron give -2.77 ± 0.12, in good agreement with the energy spectrum of protons and He nuclei, as obtained by Ryan et al., 1972 [10] and the JACEE group [9].

3. Double Diffusive Galaxy Model. We have considered a model which has characteristics of both the two component models previously discussed, the nested leaky box model (Cowsik and Wilson, 1973) [11] and the closed galaxy model (Peters and Westergaard, 1977) [12]. The model is characterized by two leaky boxes one inside the other as in the nested leaky box model. The observer is inside the inner box as in the closed galaxy model. Particles are held in both boxes by diffusive scattering and so both boxes would act like leaky boxes. The inner box represents the local interstellar region and the local sources. The lifetime of particles within this source region would be given by the ^{10}Be observations and the mean matter traversed would be that given by the HEAO-3 observations of B and C, N, O elements. The nuclei observed from a local source region would be relatively young. The composition consists of heavy nuclei.

The outer box would be the galaxy and its halo. This outer box would contain "old" particles, including protons and their secondary antiprotons. Particles would propagate therein under the control of a diffusion coefficient which has the same rigidity dependence as in the inner box, namely, scattering controlled by magnetic inhomogenieties. This would be required by the observation that the proton spectrum is assymptotically the same as those of the heavier nuclei, i.e., $\gamma \approx 2.75$. The matter traversed by particles in this outer box would have to be about three times that of the inner box. Since the mean density is much lower, the lifetime in the outer box would have to be 50-200 time longer than in the inner box.

The source spectra would be given by shock acceleration and the equilibrium spectra observed would be steepened by the energy dependent diffusion in both boxes. This model would remove any conflict between the low energy composition data and the high energy isotropy, which is determined by the conditions in the outer box. The 1 GeV/amu particles observed at Earth contain "young" heavy nuclei from nearby sources ($\lesssim$ 0.5 kpc) and "old" protons and helium nuclei from the galaxy as a whole.

We may be effectively outside the source of the very lowest energy particles (~ 100 MeV/amu) because, at this low energy, the diffusion coefficient will be very small. This could explain the increasing truncation of the path length distribution below 1 GeV/amu (Wefel et al.).

4. Discussion. Remembering that these results are preliminary, one can note that if iron secondaries do increase at high energies, the conventional leaky box with a monotonic decrease of matter with energy will need modification to account for the ratio of Fe secondaries/Fe at high energies. The antiprotons detected (Golden et al., 1979) [3] do need more matter traversal than the leaky box model would allow. Cowsik and Gaisser 1982, [13] postulate separate sources for antiprotons and heavy nuclei. The normalization of the strengths of these sources would depend on the relative amounts of antiprotons, secondary, and primary heavy nuclei. Various considerations of the nature suggest a two component model for the propagation of cosmic rays.

A leaky box like the outer box with a mean matter traversed would produce an iron secondary to iron ratio approximately twice that of a $7 g/cm^2$ inner box, but both boxes produce a ratio which falls with increasing energy due to the energy dependence of the diffusion coefficient. It, therefore, seems to be difficult to find an admixture of the relative abundances of iron from the two components that could produce a sub-iron to iron ratio which would increase with energy unless the outer box contributes only at higher energy. This could be the case probably only if the relative size of the diffusion coefficient were contrived in the same manner.

In conclusion, it seems difficult to match the increase in the sub-iron to iron ratio with a shock acceleration model including a local source on a general galactic background without introducing a new parameter, namely, the variation of diffusion coefficient with position in the galaxy. Of course, the closed galaxy model itself requires source spectra which are as steep as proton spectrum. One variant of this model might be that high energy particles can penetrate into regions of dense matter. This is the functional equivalent of having a diffusion coefficient which is contrived in a manner which allows higher energy particles to pass through more matter.

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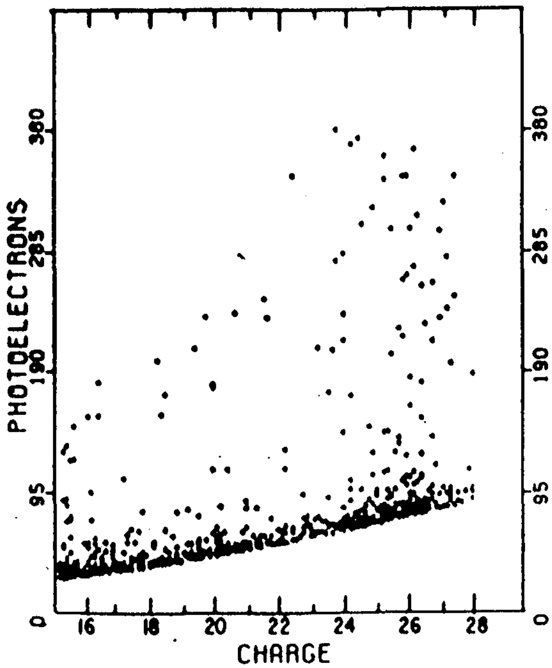

Figure 1