

IMPLICATIONS OF THE EXPERIMENTAL RESULTS ON HIGH ENERGY
COSMIC RAYS WITH REGARD TO THEIR ORIGIN

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1. Introduction. In an earlier paper at this conference (OG5.4-4) by Linsley and Fichtel (1985), it was shown that current cosmic ray evidence supports a change in the cosmic ray composition in the region between 10^6 and 10^8 GeV total energy in the direction of a smaller average value of A. Compared to normal celestial abundances, the heavy nuclei are much less abundant, and, in fact, the composition measurements above 10^8 GeV are consistent with there being only protons. Here, these results combined with those of the energy spectrum and anisotropy of the cosmic rays and other astrophysical information will be examined to try to determine their implications for the origin of the cosmic rays. In the next two sections, there will be a consideration of the implications of one or more than one type of source in the galaxy to see which are consistent with the interpretation of current measurements. In the last section, the nature of the source types that would be required are discussed.

2. Consideration of a One Source Type. These sources would presumably be distributed throughout the galactic plane. The possibility of a single source at the galactic center or elsewhere is a special case. The most likely possible sources of cosmic rays, at least for the lower energies (10^6 GeV), appear to be supernovae and pulsars. Since the models generally envision the acceleration of the outermost layer (in the case of a supernova) or surrounding material (for a pulsar), there is not a major problem in reproducing the observed composition at lower energies at least in broad terms when subsequent fragmentation in the interstellar medium is considered.

Figure 1 summarizes current information on the observed total energy spectra. It is clearly not possible to obtain agreement with the all particle energy spectrum by assuming that all types of particles have an energy spectrum that continues as a power law with the same slope to arbitrarily high energies. It is also not reasonable to expect this to occur if these particles are galactic, because, even if they have such a spectrum at the source, there is a rigidity above which they cannot be held easily in the galactic arms in the plane (Peters, 1959; Fichtel, 1963). Using an estimated magnetic field value based on current information that is slightly smaller than used in the latter paper, that rigidity is estimated to be between 10^6 and 10^7 GeV. Clearly the steepening in the all particle spectrum at or somewhat below 10^7 GeV is consistent with this concept, and the change in slope at 10^{10} GeV (actually suggested by Fichtel, 1963, before it was reported by Linsley, 1963) may suggest an extragalactic component, although other

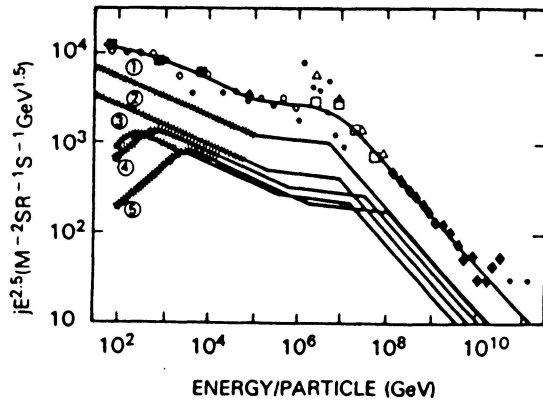


Fig 1: Cosmic Ray Particle Intensity as a function of kinetic energy per particle. The references corresponding to the symbols in the figure for nuclei of all types are as follows: closed square, Ryan et al.

(1972), Simon et al. (1980); and Burnett et al. (1983a); closed triangle, Burnett et al. (1983b); open circle, Grigorov et al. (1971); asterisk, Kristiansen et al. (1983); open square, Efimov and Sokurov (1983); open triangle, La Pointe et al. (1968); closed diamond, Cunningham et al. (1980); closed circle, Bower et al. (1983). The circled numbers refer to the following 1 H (protons); 2 He; 3, (C,N,O); 4, (10 < Z < 20); 5, (21 < Z < 30). The hatched portion (++++) of the curves are based on a large number of balloon flight results, including: Ormes and Webber, (1965); Freier and Waddington, (1968); Lezniak and Webber, (1971); Webber et al. (1972); Ryan et al. (1972); Ormes and Balasubrahmanyam, (1973); Juliusson, (1974); Fisher et al. (1974); Arons and Ormes, (1975); Julliot et al. (1975); Lund et al. (1975); Fisher et al. (1976); Hagen et al. (1977); Caldwell and Meyer, (1977); Maehl et al. (1977); Weber et al. (1977); Wefel et al. (1977); Lezniak and Webber (1978); Garcia-Munoz et al. (1979); Simon et al. (1980). The remainder of the curves are the cosmic ray particle intensity spectrum predicted for a single source model with a rigidity dependent escape, as explained in the text.

explanations are possible. Spectra which continue as a constant power law until a rigidity where particles begin to escape clearly, however, will not explain the moderate flattening of the spectrum from 10^5 to almost 10^7 GeV. As one approaches the rigidity where particles escape relatively easily, it is not unreasonable in a trapping and diffusion region to expect a lessening of the escape rate just below the rigidity where escape becomes relatively easy, as a result of the rigidity being large enough so that the smaller irregularities in the field are in effect not being seen by the particles. There must, of course, also not be a high intensity of large scale irregularities. One does not know if this is the situation, but it is at least plausible.

For Figure 1, a one source model was chosen with a power law of the form

$$j_z = A_z E^{-a} \quad (1)$$

for energies above the rounded portion of the maxima, and with the relative abundances shown as deduced from the balloon instrument results. The slope in Figure 1 may be interpreted as consisting of two parts, a and b, where a is given by equation (1) and b is a rigidity dependent escape term, as suggested by Ormes and Protheroe, (1983). Below 10^5 GeV, but above the rounded portion at low energies, the value of (a+b) used in Figure 1 is 2.7. Following this thinking and that of the last paragraph, b then decreases somewhat as escape becomes slightly less likely at 10^5 GeV and then increases markedly at 5×10^6 GeV. The values of (a+b) used in Figure 1 are 2.55 and 3.05 for $10^5 \text{ GeV} < 5 \times 10^6 \text{ GeV}$ and $R > 5 \times 10^6 \text{ GeV}$ respectively. It is now known (see, for example, Linsley, 1983) that there is an energy dependent anisotropy, which is consistent with a galactic population up to about 10^{10} GeV.

The measurements of the composition, or more exactly, the average value of the logarithm of the number of nucleons per nucleus, were discussed by Linsley and Fichtel (1985). The determined values of $\langle \ln A \rangle$ as a function of energy are shown in Figure 2 together with the variation of $\langle \ln A \rangle$ with energy predicted by the energy spectra shown in Figure 1. Clearly the curve, (a) in the figure and the data do not agree. It should be noted that the general shape of this curve, that is the rise to a higher value and then a leveling to a constant, is a result of the same source energy spectra for all nuclear species and a rigidity dependent escape. It does not depend significantly on the

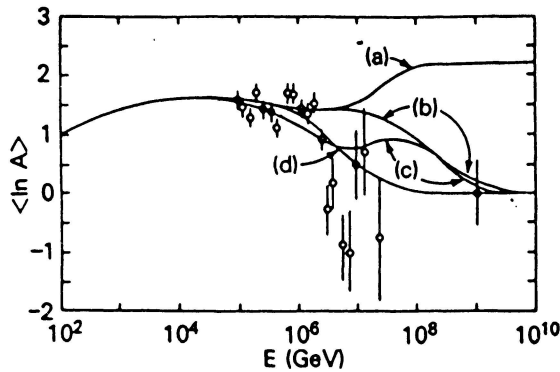


Fig 2: The average value of $\ln A$ as a function of particle kinetic energy. Closed square, Burnett et al. (1983b); open circles, Acharya et al. (1983) with $\langle N_p \rangle$ converted to $\langle \ln A \rangle$ using simulation results given by Acharya (1983); closed circle, Linsley and Watson (1961). Due to the experimental errors some of the open circles fall below $\langle \ln A \rangle = 0$, in formal violation of the astrophysical constraint, for primary nuclei, that $\langle \ln A \rangle$ should be zero (pure protons) or greater. The results below 10^4 GeV are normalized to the balloon results listed in the caption of Figure 1. Curve (a) refers to the single source model discussed in the text, whose spectra are shown in Figure 1. Curve (b) refers to a single source model in which the highest energy particles pass through much more matter. Curve (c) refers to the two source type model discussed in the text, wherein the spectra of both sources change at 3×10^6 GeV/C due to escape from the arms. Curve (d) refers to the two source type model discussed in the text, wherein one source has truncated spectra, which are shown in Figure 3.

source spectral shape. A possibility for a change in the composition of the type observed in a single source model is that it is a propagation effect. If, as seems almost certain, the magnetic fields in the Galaxy beyond the galactic arms are significantly weaker than in the arms and the matter density beyond 1 kpc from the plane is small, $<10^{-2} \text{ cm}^{-3}$, then the cosmic ray saturation density for the galaxy is well below that in the arms, and the lifetime is such that the matter traversed is very much less than that required to give the fragmentation of the heavy nuclei needed to cause predominantly heavy-nuclei-free cosmic ray composition above about 10^7 GeV.

3. Two Source Type Models. The introduction of two-source models is naturally aimed at avoiding the difficulties that have just been described. The discussion in this paper will be restricted to galactic sources being in the plane. Even subsequent acceleration models, which would not address the composition change at 10^6 to 10^7 GeV, are generally discussed in terms of the galactic plane. The basic concept which seems plausible is that one type of source dominates below about 10^6 GeV and the other above about 10^7 GeV with there being an overlap or transition region. As the apparently simplest assumption, the source type supplying the lower energy region will be taken to have the characteristics of the one-source-type model, but with no change in spectral slope until the escape from the galaxy. It will be assumed that the source at high energies, consisting of protons or mostly protons, whatever its origin, has a smaller slope, but also being a diffuse galactic source must have its steepening at the same rigidity as the lower energy type of source and by the same amount. An example of the results of this approach is shown in Figure 2 as curve (c), wherein the increase in slope due to escape from the arms occurs at 3×10^6 GeV/C and the slope increases by 1.0 for all spectra. The energy spectrum matches well and the predicted $\langle \ln A \rangle$ as a function of energy comes closer to the experimental values.

From an examination of the experimental data, however, it would appear that the composition may change at a somewhat lower energy; hence, either the escape rigidity must be overestimated or the lower energy source must not accelerate particles efficiently to quite this rigidity. If the escape rigidity is lowered significantly, it is not possible to obtain agreement with the total energy spectrum unless a more complex energy spectrum is assumed for the high energy source. The result for the total particle energy spectrum obtained by assuming that the lower energy cosmic ray spectra changes slope at 5×10^5 GeV, while

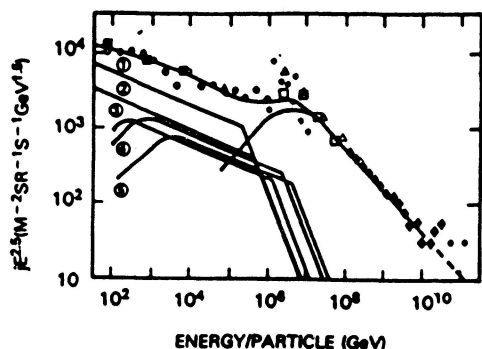


Fig 3: Cosmic ray particle intensity spectrum predicted by a two source type model in which the dominant low energy source has a source spectral change at 5×10^5 GeV and the high energy source reflects a spectral slope change at 5×10^6 GeV due to the effect of escape. The data are those referenced in Figure 1.

the higher energy source spectral change due to escape from the arms is around 5×10^6 GeV, is shown in Figure 3. The predicted behavior of the composition $\langle \ln A \rangle$ vs E is shown as curve (d) in Figure 2. There is good agreement here with this broadened set of assumptions. Also, the increasing anisotropy is consistent with this model as it would be with any diffuse galactic source model as noted earlier. Should $\langle \ln A \rangle$ not decrease as rapidly with energy as the data in Figure 2 show, as suggested by Nikolski and Stamenov (1983) and Dyakonov et al. (1983), the conclusions with regard to the nature of the two source types would be unchanged except that the higher energy source type would have more heavy nuclei. The significant point is that an acceptable two-source-type model seems possible.

4. What are the Two Source Types. As noted earlier, there seem to be several plausible theories to explain the cosmic rays comprising the component below about 10^6 GeV. The source of higher energy galactic cosmic rays must be able to accelerate particles to 10^{10} GeV. Further, this component is probably dominated by protons or may at most be a mixture of protons and relatively small amounts of helium and heavy nuclei compared to the celestial normal abundances. With regard to the composition, there seem to be at least two ways in which it might be achieved; the source could be a basically proton source (or produce neutrons which decay to protons), or the source could have a normal composition, but the particles could subsequently traverse enough material or photons in the source region to cause sufficient fragmentation of the heavier elements to leave a mixture of largely protons and some helium nuclei at least for part of the energy range. Possible source models include one associated with pulsars, although the highest energies are a difficulty, and a rapidly rotating massive black hole at the galactic center.

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