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Extragalactic heavy nuclei in cosmic rays?

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Abstract. It might be thought that if the energetic particles in the cosmic radiation are of extragalactic origin then they must be protons because heavy nuclei would be completely fragmented by interactions with the radiation fields in space. Here we argue that this is not the case and that it is, in principle, possible to choose an origin model in which the very energetic particles commence their life as heavy nuclei; these nuclei then interact with extragalactic photons and give rise to the observed primary spectrum. Such a model would relate mainly to energies above about 10^{18} eV where there is the well known need to postulate extragalactic origin on the grounds of the observed near-isotropy of arrival directions.

Specific experimental tests of models of this type are suggested

1. Introduction

The problem of the origin of the cosmic radiation is a continuing one. At energies in the region of 10^9–10^{10} eV there is circumstantial evidence for the presence of energetic particles, protons and/or electrons, in supernova envelopes but at higher energies there is still obscurity. The main reason is the presence of magnetic fields in the Galaxy which cause a virtually complete lack of correlation of the arrival directions of the charged particles, which comprise the bulk of the radiation, and the directions of the sources from which they originated. Quantitative work on the trajectories of charged particles has been carried out by Karakula *et al* (1972) and these authors showed that above about 10^{19} eV the Galactic deflections should be rather small unless the particles are heavy nuclei or the magnetic field configuration in the Galaxy is very different from that usually assumed. Thus, studies at these very high energies might be expected to give a clue as to the origin of the particles; at least one would expect to be able to distinguish between the extreme models of Galactic and extragalactic origin.

Until very recently, the experimental data above 10^{19} eV appeared consistent with complete isotropy (eg Linsley and Watson 1974), an observation that would strongly suggest extragalactic sources but the work of Krasilnikov (1974) and Krasilnikov *et al* (1974) has given evidence for a quite large anisotropy of arrival directions. However, the anisotropy claim has been queried on statistical grounds by Kiraly and White (1975) and we feel unable to accept it as yet. Furthermore, even if the claim is accepted, its interpretation is not clear: Krasilnikov *et al* themselves incline towards the view that the particles are from extragalactic sources whereas Hillas and Ouldridge (1975) give an interpretation by way of Galactic sources.

Our own view is to take extragalactic origin as the more likely at present and here we follow up one aspect of the problem: the question of the mass composition of the particles at their origins and the way in which it is affected by propagation effects so as to give the composition (and energy spectrum) of the primaries, ie those particles which appear at the top of the earth's atmosphere.

The analysis is similar, in a sense, to that in a recent paper (Strong *et al* 1974a, to be referred to as I), where we examined the possibility of the majority of primary cosmic rays above about 10^{17} eV being protons of extragalactic origin. An attractive feature of that model was the fact that, starting with a spectral shape at production having a constant exponent ($j(E_{\mathrm{p}}) \propto E_{\mathrm{p}}^{-2\cdot75}$) and the absolute intensity as measured at about 10^{10} eV, it was possible to reproduce rather well the measured primary spectrum above 10^{17} eV. The reason for the agreement with the measured spectrum, which has a differential exponent in the region of 3·0–3·2 above 10^{17} eV, is that the 2·7 K radiation field causes, by way of electron pair production and pion production, the necessary increasing attenuation of intensity. An even better fit to the experimental intensities above about 5×10^{19} eV was shown to follow (Strong *et al* 1974b) by making the reasonable assumption that there is an enhancement of cosmic ray intensity in the supercluster such as would follow from the higher than 'average' density of galaxies in this region.

A test of this model would be the identification of protons alone throughout the energy range in question, identification of the accurately predicted spectral shape, characterized by a slow increase in exponent above about 10^{20} eV, and the observation of an anisotropy: perhaps an enhancement towards the Virgo cluster. Unfortunately, such tests have not yet proved possible experimentally.

In the present paper we use essentially the same approach to examine the possibility that the majority of the highest-energy cosmic rays are produced in extragalactic sources as high-mass particles rather than protons, the production spectrum again having a near-constant exponent.

Insofar as iron occupies a unique place in nucleosynthesis the case of generated iron is considered first; similar analyses could be made for other generated nuclei (and results are in fact also derived for oxygen nuclei as possible 'intermediate nuclei'). It is relevant to remark that some acceleration mechanisms would accelerate heavy nuclei preferentially (see Ginzburg and Syrovatsky 1964 for a discussion of this problem) and of course evolved astronomical objects contain higher than average abundances of heavy elements. Specific suggestions have been made for strong iron sources in pulsars (Gold 1975) and supernova envelopes (Colgate 1974 and others) although it is not suggested that the sources of the iron nuclei to be considered here are these objects.

It is necessary to state at this stage that the sources must differ from those responsible for the bulk of the low-energy primary cosmic rays because, as is well known, the majority of the observed primaries below about 10^{13} eV/nucleon (and perhaps higher) are protons and not iron nuclei. It is fair to say that above 10^{17} eV, the region of prime concern here, the mass composition of the primaries is as yet unknown.

Although the purpose of the present paper is simply to draw attention to the need to take seriously the possibility of very energetic extragalactic cosmic rays being derived from heavy nuclei it is useful to formulate a specific model to illustrate the arguments. A plausible origin model involving iron is one in which the bulk of the observed flux of (low-energy) iron nuclei is of extragalactic origin and many of the secondary, lighter nuclei would then arise from fragmentation of these iron nuclei during a period of the order of 10^6 yr in which they would be trapped in the Galactic magnetic field (Shapiro and Silberberg 1975 have made detailed studies of the fragmentation process for various nuclei traversing interstellar matter). A refinement of the model is one in which the other, non-secondary, primary nuclei (such as carbon and oxygen) are also of extragalactic origin and propagation of oxygen will also be considered to some extent (oxygen is taken as representative of the CO group).

Of course, the true situation could be more complicated than the model suggests with perhaps only a fraction of the measured heavy nucleus flux at 10^{10} eV/nucleon or so coming from extragalactic sources but the arguments that follow would not be invalidated.

2. The assumed production spectrum

As a start one could take the measured spectrum of iron nuclei as the reference and extrapolate it continuously to higher energies with constant exponent; the likelihood of a production spectrum having a constant exponent over a very wide range of energy was discussed in I. Unfortunately there is some doubt as to the actual form of the low-energy iron spectrum, different experiments giving somewhat discordant results and all that can be said is that the integral exponent probably lies in the range $1{\cdot}1 < \gamma_i < 1{\cdot}5$. It will be shown later that with $\gamma_i = 1{\cdot}5$ the final intensity near 10^{19} eV is quite close to observation, after modulation by the interactions to be described shortly. Thus, calculations will be made for γ_i values in this region, and the intensities will be normalized (but only by displacing the intensities by comparatively small amounts) to observation at 10^{19} eV; if, to get good agreement over the important energy range 10^{18}–10^{20} eV, a smaller value of γ_i is required then this could be interpreted as indicating that only a part of the observed low-energy flux of heavy nuclei is of extragalactic origin (extrapolation back, with constant γ would give an intensity at 10^{10} eV/nucleon below observation).

In the model, evolutionary effects are ignored and we assume that the production spectrum has constant magnitude out to the classical radius of the universe. This is equivalent to assuming that the sources of cosmic rays were not of higher intensity at small red shifts. The procedure follows that of our earlier work (I).

3. Radiation fields in the universe

Apart from the 2·7 K radiation field the extragalactic fields are not known with any degree of certainty. However, following Allen (1973) and the summary given by Wdowczyk *et al* (1972), we take the following as indicating likely orders of magnitude for the energy densities: optical at 3×10^{-2} eV cm^{-3}, 2·7 K radiation at $2{\cdot}4 \times 10^{-1}$ eV cm^{-3} (Allen quotes $3{\cdot}9 \times 10^{-1}$ eV cm^{-3} for the microwave radiation which presumably contains a contribution from the infrared) and the infrared radiation at $2{\cdot}4 \times 10^{-2}$ eV cm^{-3} (following Encrenaz and Partridge 1969). It must be reiterated that there can be no question of these figures being accurate but they have been chosen because they are the most recent; they do not represent the results of any *a priori* selection.

4. Rates of energy loss in the radiation fields

Nuclei interacting with photons lose energy by electron pair production and pion production; they can also be removed from the beam completely and appear as 'new' lighter nuclei by fragmentation.

The fragmentation process will be considered first. To sufficient accuracy the process can be considered as one in which single nucleons are knocked off the original nucleus in encounters with photons, these nucleons having the same Lorentz factor as the parent nucleus. Of course, reactions occur in which more than one nucleon is released, but these have higher thresholds and the rapidly falling energy spectrum always causes low-energy processes to be at a premium. (As an example of the energy thresholds Bishop and Wilson (1957) give $E_t = 15{\cdot}9$, $18{\cdot}7$, $27{\cdot}4$ and $32{\cdot}0$ MeV for (γ, p), (γ, n), (γ, pn) and $(\gamma, 2\mathrm{n})$ reactions with $^{12}\mathrm{C}$ as target.)

A useful summary of the cross sections and other parameters for γ–nucleus reactions has been given by Kinsey (1957). It is shown that for the mass range in question here, $A \leqslant 56$, the integrated cross section (in MeV b) for (γ, n) and (γ, p) reactions is represented by

$$\int_0^{100\,\mathrm{MeV}} \sigma(E_\gamma)\,\mathrm{d}E_\gamma \simeq 0{\cdot}06\frac{NZ}{A}$$

(for example, $(A/NZ)\int_0^{30}\sigma(E_\gamma)\,\mathrm{d}E_\gamma = 0{\cdot}045$, $0{\cdot}043$ and $0{\cdot}048$ for $^{56}\mathrm{Fe}$, $^{12}\mathrm{C}$ and $^{2}\mathrm{D}$ respectively). Insofar as NZ/A is approximately proportional to A over this range the integrated cross section is about $0{\cdot}015A$ MeV b.

Starting with the case of iron, a sufficiently accurate expression for the giant resonance cross section is

$$\sigma(\epsilon, \mathrm{Fe}) = \frac{\sigma_0(\mathrm{Fe})}{[(\epsilon^2 - \epsilon_0^2)/\epsilon T]^2 + 1}$$

where $\sigma_0 = 1{\cdot}16 \times 10^{-25}\,\mathrm{cm}^2$, $T = 6$ MeV and $\epsilon_0 = 18{\cdot}25$ MeV. This has been used in conjunction with approximate expressions for the spectral forms of the radiation fields to give the mean free path for fragmentation $\lambda(\mathrm{Fe})$ as a function of energy. The results are given in figure 1, where λ^{-1} is plotted against energy. The result for fragmentation on the 2·7 K radiation is reassuringly close to previous, independent values given by Stecker (1969). (It should be pointed out that this author, too, has examined some of the implications of fragmentation of extragalactic heavy nuclei.)

Also shown in figure 1 is the reciprocal 'classical' radius of the universe, R^{-1}, a quantity which is also equal to the fractional rate of energy loss $-(1/E)(\partial E/\partial x)$ due to expansion (a Hubble constant of $60\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ has been adopted).

Calculations have been made for lighter nuclei in a similar fashion adopting the relation

$$\sigma_0(A) = 2{\cdot}07 \times 10^{-27} A\,\mathrm{cm}^2$$

based on the arguments advanced in the previous paragraphs.

In the calculation of the propagation of the various nuclei through the universe attention is confined largely to particles of total energy below 10^{20} eV (where the 2·7 K radiation is unimportant) and it is sufficiently accurate to use a linear relationship between the reciprocal mean free path λ^{-1} for fragmentation and particle energy, as shown in figure 1. The expression for iron is $\lambda^{-1} = 1{\cdot}35 \times 10^{-39} E^{2/3}\,\mathrm{cm}^{-1}$. In view of the approximate linearity of $\int \sigma(E_\gamma)\,\mathrm{d}E_\sigma$ with A the mean free paths for other

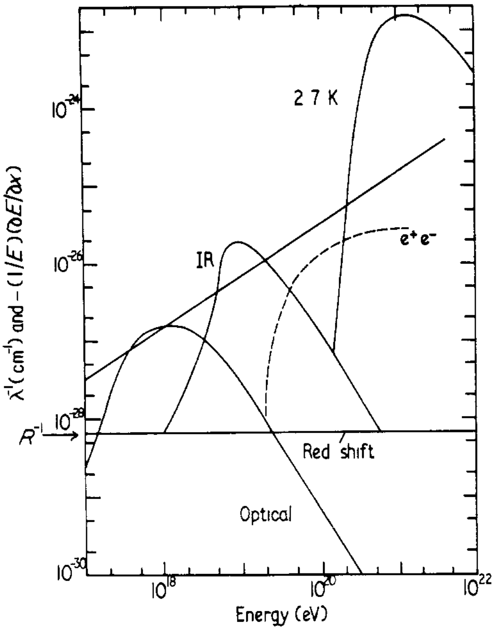

Figure 1. Reciprocal mean free path for fragmentation of iron nuclei on the various radiation fields. The inclined line is a rough estimate of the average value of λ^{-1} against E, valid for energies to about 10^{20} eV/nucleus. The reciprocal of the 'classical' universal radius, R^{-1}, and the fractional rate of energy loss by pair production $-(1/E)(\partial E/\partial x)$ (broken curve) are also shown. (It should be pointed out that none of the arguments put forward in the paper are particularly sensitive to the exact values for the mean free paths given in the figure.)

nuclei can be derived simply:

$$\frac{1}{\lambda(A)} = \frac{1}{\lambda(\mathrm{Fe})}\left(\frac{A}{56}\right)^{1/3}$$

Figure 2 shows this relation for selected values of A.

Turning now to the case of electron pair production for iron nuclei, only production by way of the 2·7 K radiation is important. The fractional rate of energy loss $-(1/E)(\partial E/\partial x)$ has been derived from the work of Blumenthal (1970), which relates to protons, by scaling upwards by $26^2/56$ and displacing the energy by 56. This is also shown in figure 1. Pion production is not important (for heavy nuclei) in the energy range in question.

5. Propagation of iron and its fragments through the universe

5.1. Mean free paths for fragmentation down to particular A values

For the case of iron nuclei produced uniformly throughout the universe an approximate derivation of the energy spectrum of iron nuclei which arrive unscathed at the earth to form the primary beam is straightforward using the method outlined by Strong *et al* (1974b). In this method one simply divides $BE^{-\gamma_1-1}$ by the factor given by the ratio of the total value of $-(1/E)(\partial E/\partial x)$ (from figure 1) to the redshift value (eg by ~1500 at $E = 10^{20}$ eV). However, the residual iron nuclei only represent a part of the primary

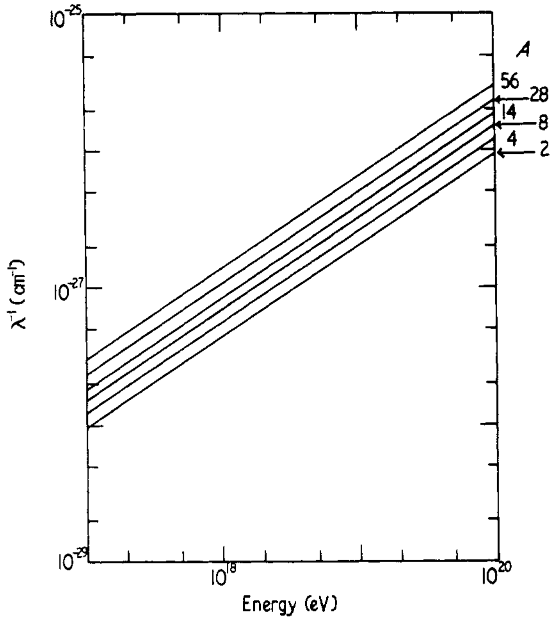

Figure 2. The average reciprocal mean free path for fragmentation against particle energy for various primary nuclei.

beam because of the fragmentation products. With the exception of the energy lost in e^+e^- production and some small amount by way of γ rays, etc generated by radioactive fragments, the total energy of the initial iron nuclei is simply redistributed amongst the fragments; in the limit, at the highest energies the bulk of the particles will be the ultimate constituent protons (the released neutrons having decayed in the very great distances involved).

In the upper part of figure 3 there are given the mean free path for iron as a fraction of R and the mean fractional distance for partial fragmentation to particles of mass $A-1$. As an example, particles of mass 40 starting from iron nuclei of energy 3×10^{19} eV have been derived, on average, from iron interacting at a distance of about 10% of R. All the quantities are given as a function of the energy of the initial iron nuclei. In the lower part of the figure there is given the ratio of the distance of partial fragmentation of iron to a particle of mass $A-1$ to the iron mean free path at the same energy per nucleon (upper curve) and at the same energy per nucleus at the observation position (lower curve). The mean distance traversed by a nucleus before it is reduced to a very low A value is seen to be rather large.

5.2. Details of the propagation calculation

An approximate analysis has been adopted in which electron pair production (and pion production for protons) is first neglected and the fragmentation process alone is considered. The energy spectrum of iron nuclei, obtained by solving the appropriate diffusion equation, has the form:

$$N(E) = [1-\exp(-CE^{\alpha}x)]\frac{B}{C}E^{-\gamma_1-1-\alpha}$$

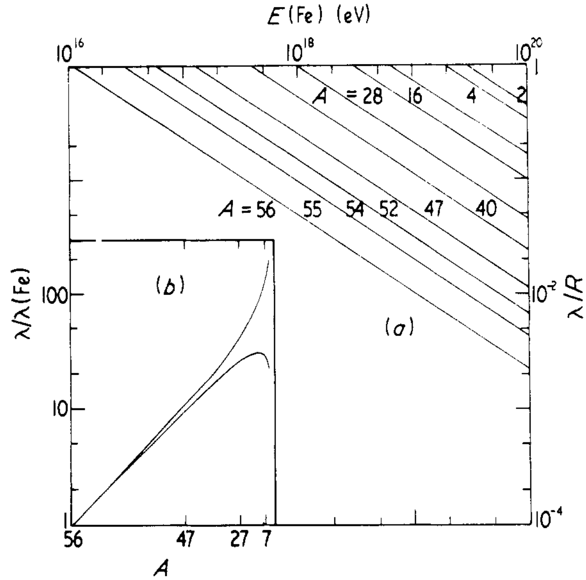

Figure 3. (*a*) Mean distance for conversion of initial iron nucleus down to a particle of mass $A-1$ divided by the radius of the universe. The abscissa is the energy of the initial iron nucleus; the energy of a residual nucleus of mass A would be $E \times A/56$. (*b*) Ratio of distance of partial fragmentation of iron down to a particle of mass $A-1$ to the iron mean free path itself at the same energy per nucleon (upper curve) and the same energy per nucleus (lower curve), the energies in question being at the point of observation.

where $BE^{-\gamma_1-1}$ is the production spectrum related to 1 cm and $C = 1{\cdot}35 \times 10^{-39}$, $\alpha = \frac{2}{3}$ and x is the distance, in this case equal to the radius of the universe. The solution for the total flux of nuclei with $A \geqslant 2$ is obtained using the information about the collection distances and considering the shape of the spectrum in the asymptotic regions. It can be easily shown that in the region where complete fragmentation occurs the total intensity is $56/(\gamma+\alpha)$ times higher than the intensity of iron for the same energy per nucleus.

The proton production spectrum has been obtained by taking the fraction of iron nuclei which completely fragment on their passage through the universe. This fraction comes from a comparison of the radius of the universe with the distance of complete fragmentation. It should be pointed out that for protons above 10^{19} eV these distances are much shorter than obtained from figure 3 as the iron nuclei were produced with energies in the region where fragmentation on the black body radiation plays an important role.

Finally, the mean mass of those nuclei with $A \geqslant 2$ is taken and a correction for pair production then applied to the spectra obtained in the first step. Similarly, corrections for e^+e^- and π production are applied to the proton spectrum.

The resultant spectrum and its component parts are given in figure 4. The results are normalized to the experimental intensities at 10^{19} eV as mentioned earlier.

5.3. Supercluster enhancement

The arguments given by Strong *et al* (1974b) suggest that in addition to a contribution from truly universal sources, ie sources distributed uniformly over the universe, some

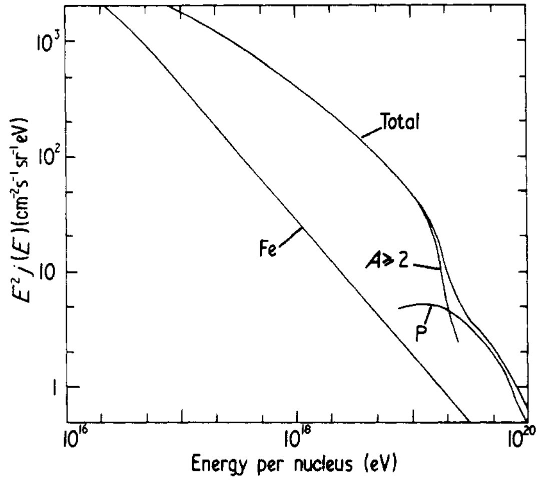

Figure 4. Predicted primary spectrum for the case of initial iron nuclei produced uniformly throughout the universe (the curves are approximate).

enhanced contribution from the local supercluster may be expected. Reasonable estimates show that this contribution may amount to about 10% in respect of the production spectrum. Assuming this value and using the same method as outlined above, the contribution from the supercluster has been calculated and added to the truly universal component. The modified spectra are given in figure 5, also normalized to the experimental intensity at 10^{19} eV.

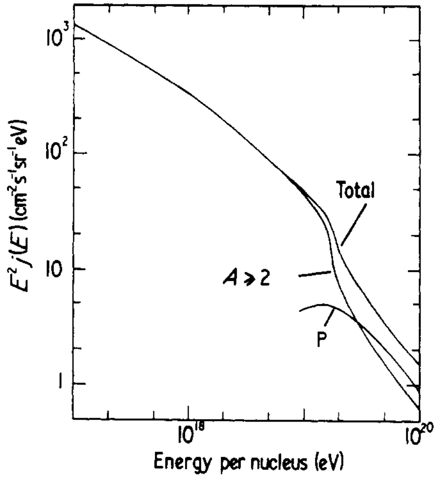

Figure 5. Predicted primary spectrum for the case of initial iron nuclei with supercluster enhancement (the curves are approximate).

5.4. Inclusion of oxygen nuclei as source particles

As mentioned in §1 the model can be refined by the addition of M-type nuclei such as oxygen; approximate calculations have been made for a number of alternative compositions (see figure 6).

6. Comparison with experiment

6.1. Spectral shape

A comparison of the various calculated spectra with the composite spectrum from Sydney and Haverah Park is shown in figure 6 (see the caption for the source of the data).

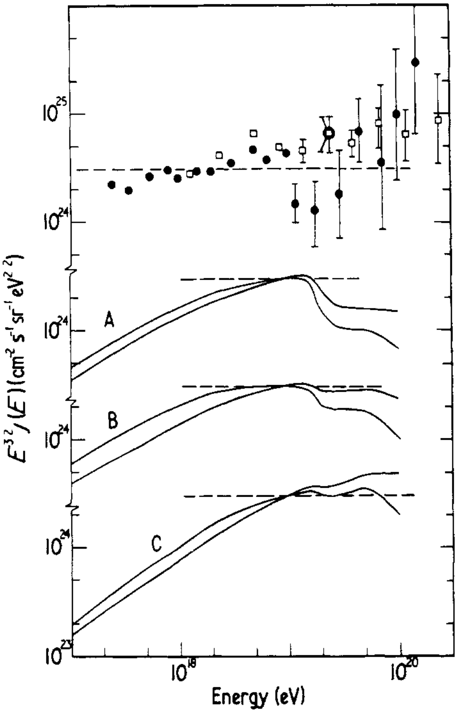

Figure 6. Comparison of observed and predicted spectra. The experimental intensities are derived by us from the basic data given by Edge *et al* (1973) (Haverah Park: full circles), Bell *et al* (1973) (Sydney: open squares). The intensities for the three lowest energy points in the Haverah Park experiment have been displaced downwards somewhat following improved analysis of the data (Edge 1975, Watson, private communication). A, $\gamma = 1{\cdot}5$, ^{56}Fe; B, $\gamma = 1{\cdot}5$, ^{56}Fe + ^{16}O; C, $\gamma = 1{\cdot}3$, ^{56}Fe + ^{16}O. (The curves are approximate.)

It can be seen that none of the predicted spectra agree with the experimental one over the whole considered interval, ie 10^{17}–10^{20} eV. However, this result is not surprising as the production spectrum was assumed to be comparatively flat (as remarked earlier the spectrum was basically chosen to match simultaneously the intensity of iron around 10^{10} eV/nucleon and the total cosmic ray flux at 10^{19} eV). As the absorption due to interaction of the produced nuclei with the radiation fields is not very significant below about 10^{18} eV it is not possible to obtain a spectrum with the necessary slope of about 2 starting from a production spectrum with slope 1·5 or less. On the other hand, moderate agreement can be obtained in the energy interval 10^{18}–10^{20} eV.

Agreement between observation and prediction is in fact slightly better for the spectrum with slope 1·3, but such a spectrum extrapolated back to 10^{10} eV gives an intensity about two orders of magnitude lower than observation in that region. The figures for the various situations are: a spectrum with $\gamma_i = 1{\cdot}5$, assuming pure iron at production, when normalized at 10^{19} eV, gives an intensity of $1{\cdot}6 \times 10^{-16}$ cm^{-2} s^{-1} sr^{-1} (eV/nucleon)$^{-1}$ at 10^{10} eV to be compared with the experimental value for iron of about $2{\cdot}5 \times 10^{-16}$ in the same units. Similarly, assuming a pure oxygen composition at production, then, under the same assumption, we obtain an expected intensity of $1{\cdot}04 \times 10^{-15}$ compared with an observed value of 3×10^{-15}, the units being the same as above. A model with 50 % iron and 50 % oxygen—or any other reasonable combination of primary masses—would thus give intensities at 10^{10} eV/nucleon at least of the order of magnitude of those measured.

Returning to the discrepancy of two orders of magnitude at 10^{10} eV/nucleon for $\gamma_i = 1{\cdot}3$, the difficulty can of course be removed by assuming that the majority of the heavy nuclei observed at low energies are of Galactic origin. However, the model then loses a certain degree of attractiveness.

Comparing the present considerations with those given in I we should like to point out that if it is assumed that the bulk of the cosmic rays at energies above about 10^{11} eV are of extragalactic origin then we require a model with protons predominating as these particles are observed to be most prominent at low energies; this was just the model adopted in I. On the other hand, if the low-energy cosmic rays are predominantly of Galactic origin and only those with the highest energies originate in extragalactic space the latter could be produced predominantly as heavy nuclei. Under that assumption in fact it is easier to obtain the correct shape of the observed spectrum at the highest energies. In such a composite model the total spectrum of cosmic rays would be obtained as the sum of a relatively steep Galactic spectrum, which may also show some irregularities and which would have the same sort of 'normal' composition as measured at low energies, and an extragalactic component with a much flatter spectrum consisting predominantly of heavy nuclei at production. The latter would only start to play a role at energies around 10^{18} eV where the Galactic proton intensity falls steeply. Such a suggestion is in fact similar to those of Berezinsky *et al* (1973) and others, although these previous suggestions have all related to extragalactic protons. The advantage of having heavy nuclei instead of protons for the very energetic extragalactic component is due to the fact that for heavy nuclei a single-slope production spectrum with an exponent of about 1·3 can account roughly for the shape of the observed spectrum between 10^{18} and 10^{20} eV, whereas if the produced particles are protons then a combination of spectra with different slopes has to be taken in order to obtain the correct spectral shape. This is true whether there is a supercluster enhancement or not. (Inspection of I is necessary in order to fully appreciate this important point.)

6.2. *Effective primary mass*

The basic test of the present hypothesis would come from measurements of the mass composition as a function of energy. As can be seen from figures 4 and 5 a rapid change of effective mass is expected around 2×10^{19} eV and this should, in principle, be detectable. In fact, the results in the figures refer to an entirely extragalactic origin with heavy nuclei at production and, as has been remarked, the spectral shape is not correct for the region below 10^{18} eV. A more reasonable assumption is that Galactic protons predominate below about 10^{18} eV in which case the effective mass will increase rather rapidly above this energy, reaching a maximum in the region of 20–30 (for 50 % Fe, 50 % O) before falling back towards lower values above about 3×10^{19} eV.

Although the mass composition of the primaries is not known at the energies in question there is hope that information will come from the various EAS arrays in operation. The data will be derived from the search for fluctuations in longitudinal development of showers and from a comparison of results taken with different arrays. Already there is evidence from the Haverah Park experiment (Watson and Wilson 1974, Lapikens 1975) which demonstrates the existence of fluctuations and indicates that at least some of the primaries are very light (protons?). Intercomparison of results from different arrays is difficult but can be profitable when the arrays respond differently to particles of primary mass. The sensitivity of detected signal to primary mass can best be illustrated by considering the muon and electron components. For the same total energy of primary particle the total number of muons at a deep observation level increases with mass number whereas the total number of electrons falls. The Haverah Park array is sensitive to a mixture of muons and electrons whereas the Sydney experiment, with its underground detectors, responds only to muons so that a comparison of accurate data from these experiments would be singularly useful. Whilst not making any claims for significance it is interesting to note in figure 6 that the Haverah Park intensities in the region 10^{19} eV are lower than those from Sydney—a result that is in the sense predicted by the previous comments for the composite Galactic–extragalactic model. Hopefully, when more precise data are available it should be possible by comparing the spectra to pronounce on the validity of the postulated model.

7. Conclusions

The analysis described in the present paper shows that the effective range of high-energy nuclei in the extragalactic radiation fields is relatively long in spite of the fact that the actual range against single fragmentation is rather short. In view of the fact that the extensive air showers initiated for instance by oxygen or nitrogen are practically indistinguishable from those initiated by iron, the distance in which reduction from a mass of 56 to a mass of around 10 is important rather than the actual range of iron nuclei. Figure 3 shows that the enhancement of length is about a factor of 30; thus, even at an energy as high as 2×10^{18} eV we can observe nuclei coming from distances comparable with the radius of the universe.

In the extragalactic origin models the shape of the energy spectrum can be made to be in fair agreement with that observed in the interval 10^{18}–10^{20} eV. This means that heavy extragalactic nuclei with a flat spectrum can account for the high-energy end of the primary cosmic ray spectrum quite adequately. Although the origin of such particles is quite obscure, some unusual galaxies or perhaps supermassive collapsed objects could be considered as candidates for sources. The mechanism of acceleration in the latter case could be similar to that of pulsars and thus a flat production spectrum might be expected. At this stage it can be remarked that, as the essential contribution of extragalactic particles to the primary spectrum is obtained only at very high energies, the results obtained under the assumption of a steady-state situation are sufficiently accurate and evolutionary effects at very early epochs should not be important.

Finally, some remarks are necessary with regard to the relative merits of our earlier suggestion, in I, that the bulk of the cosmic rays of all energies (except for $3 \times 10^{13} < E < 3 \times 10^{16}$ eV) are extragalactic protons and the arguments advanced here. If the majority of cosmic rays are in fact extragalactic then they must be mainly protons and I applies. If, on the other hand, only those above about 10^{18} eV are extragalactic (in which case the energy density of cosmic rays in extragalactic space is low and none of the usual difficulties arise on this account) then the analysis presented here shows that heavy nuclei are strong contenders; indeed, as pointed out in § 6.1 it is easier to obtain the correct spectral shape with initial heavy nuclei than with extragalactic protons.

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