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LETTER

Letter to the Editor

'Fine Structure' in the energy spectrum, and changes in the mass composition, of cosmic rays in the energy range 0.3–10 PeV

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Abstract. A recent publication by Arqueros et al. (1999), of data from the HEGRA and AIROBICC extensive air shower detector complex, updates earlier work with this apparatus (by Cortina et al., 1997). Our contention (Erlykin and Wolfendale, 1998) that the position of the knee in the primary energy spectrum had been located at too low an energy has been confirmed. The results on the 'fine structure' of the energy spectrum, a concept first put forward by us (Erlykin and Wolfendale, 1997 – and developed in later papers) – and on the dependence of mean primary mass on energy, are quite compatible with our predictions. Indeed, the new results give rather strong support to our hypothesis.

Key words: acceleration of particles – ISM: cosmic rays

1. Introduction

We have published an extended series of papers in which we claim that there is 'structure' in the cosmic ray energy spectrum in the range 1–20 PeV: Erlykin and Wolfendale, (1997), and later papers; a comprehensive paper being that by Erlykin and Wolfendale, (1998), to be denoted I. The 'structure' (or 'fine structure') – and related predictions – have a number of components, as follows:

(i) A concavity before the knee.
(ii) A 'bump' *at* the knee (at about 3 PeV) where we have argued (I) that the sharpness in the spectrum, defined as the second differential of the log intensity with respect to the $\log$ energy, is much greater than can be explained by Galactic modulation.
(iii) A second 'bump' at an energy just above 10 PeV, which we call the 'iron peak'.
(iv) An increase in the mean mass (and corresponding reduction in the P+He-fraction) of the primaries with increasing energy; specifically that, whereas the P+He-fraction is $\sim 60\%$ at 1 TeV, it falls to 40% at 1 PeV and 20% at 5 PeV.

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Although our main contention is that there is structure in the spectrum over and above the slow smooth change expected by simple Galactic modulation, we have also put forward a model to explain the results (most of which related to the size spectrum of shower particles – mainly electrons – at a variety of altitudes and zenith angles). This is as follows. We suggest that a single, local, recent supernova generated a SNR shock which has accelerated particles in the manner described by Berezhko et al. (1996), Völk (1997) and others, such that the energy spectra recorded at earth cut off sharply at $E_{\max} = 0.4$ Z PeV. The knee is identified with an oxygen 'peak' and the second bump with a peak due to iron ('peaks', as distinct from small changes in the downward run of intensity versus energy occur because of the usual practice of plotting $E^n I(E)$, where n is commonly about 3).

Irrespective of the model it is clearly imperative to decide whether there is structure at all in the spectrum or whether the spectrum simply changes in a featureless fashion, i.e. gently steepens.

Our analysis (updated recently, Erlykin and Wolfendale, 1999) uses 34 individual spectra, to be compared with 16 spectra considered in I. Our contention is that, since the vast majority of the spectra hint at structure, which is at consistent 'positions', the aggregate – in which the structure is quite clear (to us) – should be credible.

The most recent analysis is that of the HEGRA-AIROBICC group (Arqueros et al., 1999) in which Cherenkov-light-, and charged-particle-distributions in air showers are measured. Such measurements are basically important insofar as the Cherenkov observations, at least, are strongly related to the behaviour of the primary spectrum; thus the value of the measurements should be greater than 'just one more in 34'. Indeed, this work (with 42 authors) is a full description of a major project in this area, and its detailed analysis – in terms of the possibility of structure in the knee region – is surely obligatory. It is no longer adequate to show that 'there is a knee in the primary spectrum', this feature has been confirmed time and time again, since its discovery 41 years ago (by Kulikov and Khristianssen, 1958). What is needed is an *accurate* determination of its form (and the mass composition in this region) and its explanation. An analysis from our perspective will now be given.

2. The HEGRA-AIROBICC results in comparison with our model

2.1. The Position of the knee

The earlier work of Cortina et al. (1997) gave results which showed that the knee in the spectrum was at $\log E(\mathrm{PeV}) = 0.2$. In I we pointed out that this value was too low in comparison with our analysis and should be raised to $\log E = 0.5$. In the latest work, the knee has indeed been raised, to $\log E \simeq 0.6^{+0.33}_{-0.10}$ (the very high quoted upper limit is hard to understand). There is now no inconsistency with our analysis.

2.2. The sharpness of the knee

In Arqueros et al. we read that "there seems to be no "fine structure" in the energy spectrum around the knee in excess of 20%". An excess (for the point at the knee in comparison with its neighbours) of 20% would in fact correspond to a very large sharpness indeed; specifically, the result is $S = 16$ for a bin width of $\Delta \log E = 0.1$. In fact, from previous work we expect $S \sim 12$ at the altitude in question for Cherenkov measurements ($\simeq$ shower maximum) taken with the same bin. This value is clearly not ruled out by their 'allowed' sharpness.

In view of the importance of this aspect of the results we give here an analysis by us of their primary spectrum.

Arqueros et al. give four primary spectra comprising the Cherenkov data analysed two ways, and the particle data similarly treated. (They also give raw data, in the form of the size spectrum and the Cherenkov "light density at 90 m" spectrum. These will be considered later). The 'two ways' represent reconstructions of the spectra from the data assuming, alternatively, that the primaries are protons and iron nuclei.

There are, clearly, several ways in which we can proceed: to average all the data, to take averages for the Cherenkov and the Particle data separately or to take each set individually. It seems safest to choose the middle way and to derive two spectra. These will then be virtually independent.

It must be remarked that for energies below the knee the separations of the intensities inferred by the workers themselves from the same data, but with the two mass choices, are as we expect, i.e. they vary smoothly with increasing energy. However, above the knee there are some rather alarming differences in the quoted intensities which presumably arise from the Monte-Carlo-aided calculations. Hopefully, the effect of these differences is minimised when the average is used.

Fig. 1 shows the spectrum from the Cherenkov data. Also shown there is our standard set of inferred slopes and sharpness variation. The sharpness at the knee is seen to be $S = 3.8 \pm 1.1$ (for a cell width of $\Delta \log E = 0.2$), a value well in accord with what is expected from our model (if a smaller bin width had been adopted, S would have been higher still). In parenthesis it can be remarked that, if allowance were made for the undoubted observational and propagation effects, the 'true' sharpness in the primary spectrum would be very high – *much* higher than the maximum value of 0.3 expected for the standard Galactic diffusion model (see I) – and indicated in Fig. 1 by the 'GM' spectrum.

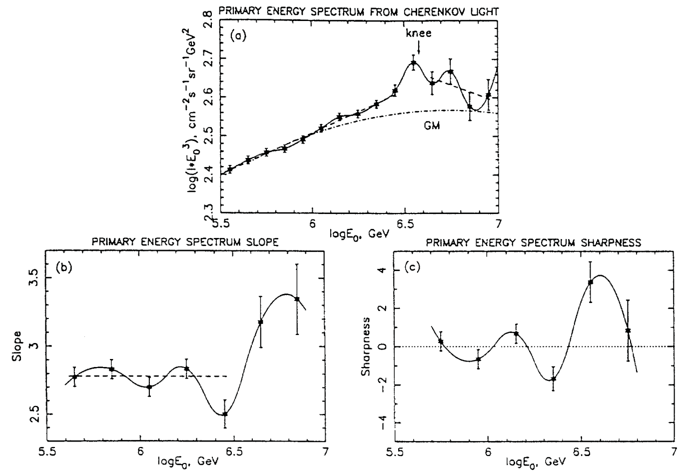

Fig. 1a–c. The primary energy spectrum from the HEGRA-AIROBICC array of Arqueros et al. (1999). We have adopted the Cherenkov results and averaged the intensities presented for alternative choices of primary particles – protons and iron-nuclei. The dashed lines below and beyond the indicated knee position are the weighted power law fits to the spectrum. The spectral slope and associated sharpness parameter, derived by us in the usual fashion (see I), and for our usual bin-width of $\Delta \log E = 0.2$, is also given. It is noted that there is a high 'sharpness' value at the knee. GM denotes the conventional Galactic Modulation spectrum, derived from I. Anything that differs from this is astrophysically interesting.

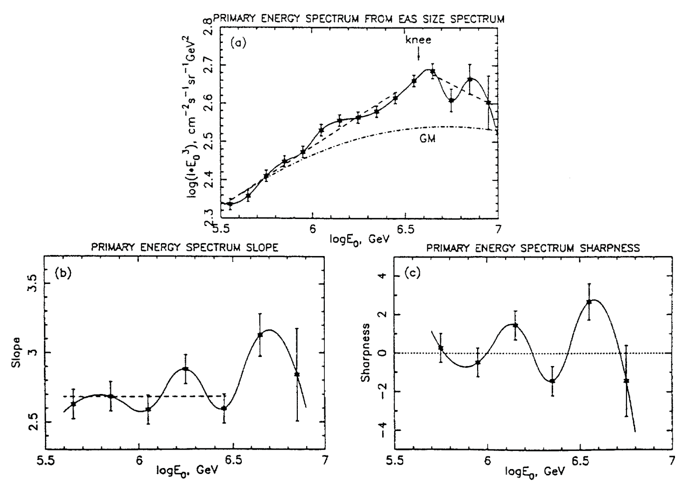

Fig. 2a–c. The equivalent plot to Fig. 1 for the HEGRA 'particle spectrum', averaging the presented results for primary protons and iron nuclei.

Turning to the HEGRA spectrum derived from the particle data, a similar analysis has been made with the result shown in Fig. 2. With the same value for $\Delta \log E$, the maximum sharpness is very similar: 2.8 ± 0.9.

It is evident that the energy spectrum results support our contention rather strongly, particularly the Cherenkov data, which

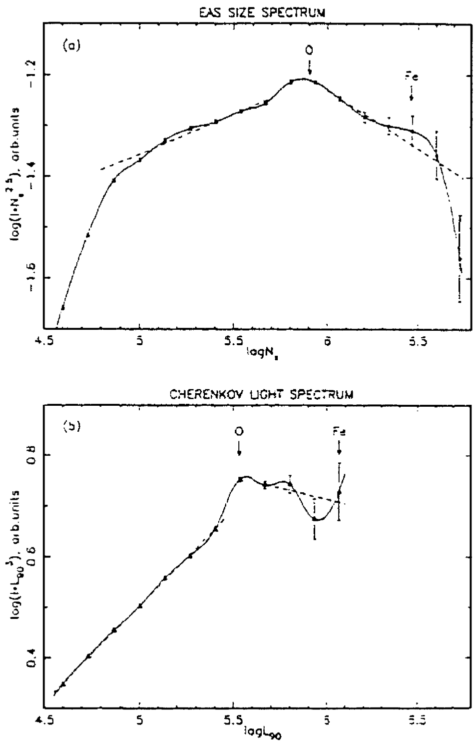

Fig. 3a and b. The differential shower size spectrum (N_S) and Cherenkov “light density at 90 m”, L_{90}, for the HEGRA experiment, as presented by the authors (Arqueros et al., 1999). The (obvious) knee position is indicated by ‘O’, and the *predicted*, by us, position of the iron-peak by ‘Fe’.

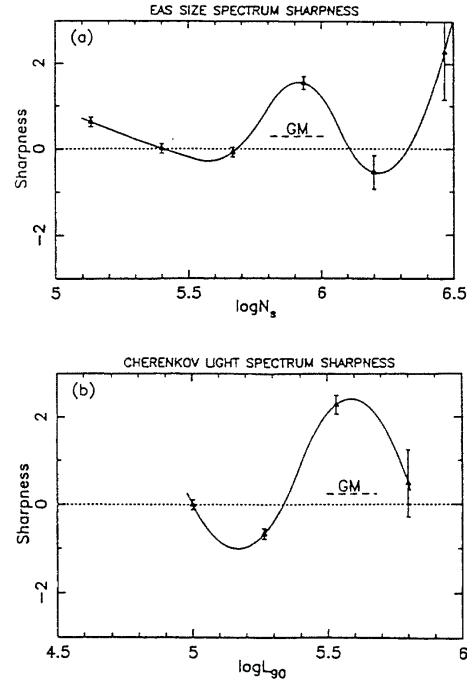

Fig. 4a and b. Sharpness versus N_S and L_{90} derived by us from the data in Fig. 3. ‘GM’ denotes expectation for the conventional Galactic Modulation model.

are generally regarded as giving a more accurate representation of the primary spectrum.

The conclusion is strengthened still further by reference to Fig. 3, which shows the HEGRA *basic data*. Starting with the Cherenkov data, although these relate only to a sub-set of the data, viz the light density at 90 m core distance (L_{90}), the intensities have smaller fractional errors on the points than the processed intensities in Fig. 1. This clearly shows that the presented intensities of the energy spectra have been degraded because of remarkably large errors in the Monte Carlo calculations. Fig. 4 shows the sharpness for N_S and L_{90}, as derived by us. Again there is support for our model.

2.3. A concavity before the knee

Figs. 1 and 2 (spectral shape and measured S-values) show some evidence in favour of our claimed concavity. There is an interval in the spectra at $\log E \sim 5.8 - -6.0$ which have negative sharpness, but the significance is not great.

2.4. The ‘iron peak’

The published (inferred) energy spectra do not extend beyond 10 PeV, where we claim the iron peak to be, and thus there is no information on this point from the combined results. However, concerning the basic shower-size spectrum and the Cherenkov ‘light density at 90 m core distance’ (Fig. 3), the former, at least, *does* go far enough beyond the knee. In the N_S spectrum our claimed ‘iron peak’ at $\Delta \log N_S = 0.56$ above the knee is clearly seen (indicated in Fig. 3). Also visible in the N_S spectrum is the drop in intensity at low sizes which is due to loss of efficiency (the workers correct for this in deriving the energy spectra).

The existence of the iron peak cannot be claimed for the Cherenkov (L_{90}) data but the intensity may well be going up as we would expect before the data cease.

2.5. The Mass Composition

Fig. 5 shows the averaged fraction of P+He in the primary beam for the Cherenkov data as given by Arqueros et al. Also shown is the result from our own work (from I). There is clearly good agreement.

There is, interestingly, support for our contention that the knee is oxygen-rich and the iron-peak is, by definition, iron-rich. This support is not visible in Fig. 5, which relates to the fraction of *light* nuclei, but comes from a detailed examination of the HEGRA plots of the distribution of depth of shower maximum. Clearly, the small maximum depth (X_m) values relate to heavy primaries and this is the region that has been studied. In the fits given by Arqueros et al. a constant mixture of 65% oxygen and 35% iron nuclei was adopted for the heavy component. Near the knee, this mixture, plus a small P+He component, fits the small X_m region ($X_m \tilde{<} 500$ gcm^{-2}) but at the highest energies: 6–10 PeV, it does not – there is an excess of observed small X_m values. A larger iron fraction is indicated. Specifically, LETTER

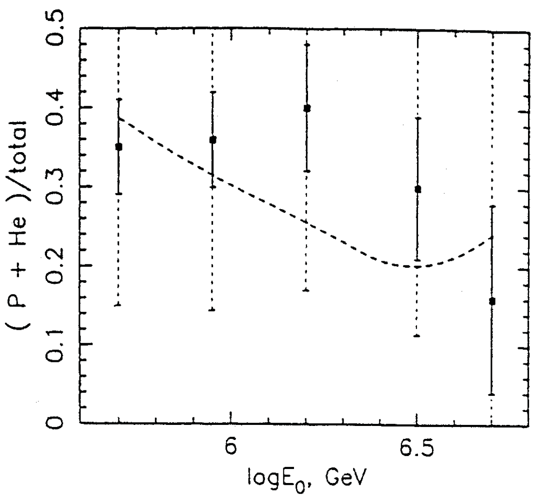

Fig. 5. Comparison of the fraction of P+He-nuclei derived from the Cherenkov data of the HEGRA-AIROBICC array (averaged by us) with that from our model (see I) – smooth line. The estimated 'errors' are: 'large', as given by the authors, 'small' as estimated by us from the dispersion of their various estimates.

for the two energy ranges in the HEGRA work relevant to the present arguments: 1.8–3.2 PeV and 5.6–10 PeV, we predict Fe/O ratios of 0.4 and 2.7. The corresponding ratio adopted by the HEGRA group is 0.54 (i.e. $35\%/65\%$) in both energy bands; our higher ratio for the highest energy band will certainly improve the fit to the frequency distribution of X_m values.

3. Conclusions

A point-by-point comparison of the results of the important HEGRA-AIROBICC experiment with our model shows good agreement. This agreement can be regarded as providing quite strong support for our main contention that there is structure in the cosmic ray spectrum in the 0.3–10 PeV region; certainly, the measured knee is far sharper than expected for the conventional Galactic Modulation Model.

It can be asked: "why did the authors not see the claimed structure?". Our answer is two-fold. Firstly, a natural conservatism, often a desirable attitude but one that is perhaps unwise if progress is to be made with a 40-year old problem. Secondly, the presentation of superimposed spectral data from the two techniques (Cherenkov – and particles –), each analysed in two ways. We argue that although systematic errors do not affect the shapes of individual spectra very much, they can be important in causing differences *between* spectra. The result is that the superposition of the spectra blurs the effect that is sought.

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