Astron. Astrophys. 356, L63–L65 (2000)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

The origin of PeV cosmic rays

A.D. Erlykin[1,2] **and A.W. Wolfendale**[2]

[1] P.N. Lebedev Physical Institute, Leninsky Prospekt 53, 117924 Moscow, Russia
[2] University of Durham, Physics Department, Durham, DH1 3LE, UK

Received 8 December 1999 / Accepted 18 March 2000

Abstract. The search for the origin of cosmic rays is a continuing one. The energy range covered is immense: 10^9 eV to 3.10^{20} eV, and perhaps beyond. Only at the lowest energies ($10^9 - 10^{10}$ eV) have analyses of gamma rays (e.g. Osborne et al., 1995) shown that supernova remnants are probably important – above this there is great uncertainty. In a series of papers, we (e.g. Erlykin and Wolfendale, 1997a) have claimed that a 40-year old property of the cosmic ray energy spectrum at $\sim 3.10^{15}$ eV (3 PeV) – the so-called 'knee' – is in fact a complex feature that is strongly related to the origin mechanism. Specifically, we have made the case for the feature being due to a single, recent, local supernova. The case has not been accepted by the community, hitherto, but here we present very recent results which complement those analysed earlier and give, in our view, support to the hypothesis; at least for the contention that there is structure. We have now seen the same, complex, feature in every aspect of the cosmic radiation that we have examined.

Key words: acceleration of particles – ISM: cosmic rays

1. Introduction

The energy spectrum of cosmic rays must, in principle, have, within it, some features which are related to production mechanisms as distinct from the ubiquitous propagation characteristics. So far, however, only two features are generally agreed: the 'knee' at $\sim 3.10^{15}$ eV and the 'ankle' at $\sim 5.10^{18}$ eV. Concentrating on the knee, it is generally assumed that this results from 'Galactic Modulation'. However, our firm contention (Erlykin and Wolfendale, 1998a) is that the knee is far too sharp to be explained in this way; such Galactic propagation characteristics as appear reasonable would give only a slowly steepening spectrum assuming, as is usually done, that the injection spectrum can be represented by a simple power law.

Our analysis (Erlykin and Wolfendale, 1997a,b,c; 1998a,b,c; 1999a,b; Erlykin et al., 1998) of the world's data on extensive air showers (EAS), from which the primary energy spectrum can be derived, has led us to claim that the knee is not just a single sharp feature but that it has further structure, specifically that the spectrum has, essentially, two knees. Most of the data analysed so far have comprised EAS measurements in which the predominantly electron component is recorded. Despite the inevitable fluctuations in particle number associated with this technique we have found evidence for the claimed feature in most of the 40 individual size spectra (from 17 experimental arrays) examined. The lack of acceptance by the community stems from the fact that in most of the individual spectra the effect is weak and usually not significant; it is only by combining the data from the different experiments that the effect really shows up.

The energy spectra for the various components in the original version of our model are shown in Fig. 1. 'SNR' denotes the components assumed to be generated by a single supernova remnant which is accelerating particles from the hot interstellar medium (this supernova has not yet been identified, although there are candidates (Erlykin et al., 1998)). It will be noticed that the first knee is attributed to oxygen and the second knee is due to iron nuclei. The characteristic spectral shapes of the spectra and their energy cut-offs come from a recent SNR acceleration model (Berezhko et al., 1996) for particular input parameters (magnetic field in the ISM etc.). It is the heights of the spectra which are chosen by us to fit the (previously analysed) data.

It should be pointed out that the original spectrum (shown) was taken to fit the measured sharpness of the size spectra ('sharpness' is the second differential of log (Intensity) versus log (Size)). The 'background' was chosen to fit direct intensity measurements at much lower energies and intensities inferred from data above the knee region, corresponding to energies above about 50 PeV. A particular, and to us reasonable, mass composition was assumed for the background; the various components w taken to join smoothly to their respective spectra at much lower energies, where direct observations have been made, and 'our' Galactic Modulation factor (see Erlykin and Wolfendale, 1998a) has been adopted. We have demonstrated (Erlykin and Wolfendale, 1998b), to our satisfaction, at least, that the mean mass varies with energy, for the model, in a similar manner to that inferred from the experimental data.

The size spectra examined in the early work numbered 17, i.e. less than a half of the number currently available. Inevitably the inferred energy spectrum from the current data set will be somewhat different from the 'EW' spectrum given in Fig. 1 but

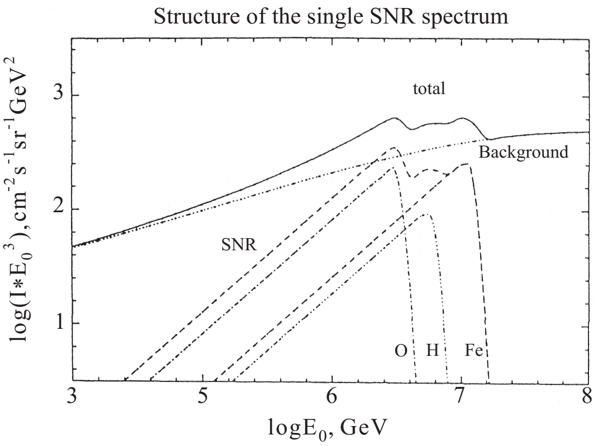

Fig. 1. Best fit components of the primary energy spectrum for the EW model (e.g. Erlykin and Wolfendale, 1998a). ‘SNR’ denotes the component from the local, recent supernova (as yet unidentified) which gives the shock which, in turn accelerates the detected particles. The ‘background’ is assumed to be derived from many other sources.

it will preserve its basic features – two sharp knees due to oxygen and iron peaks – and we persist with EW for reasons of consistency.

2. The analysis of new measurements

Very recently, new measurements have been reported which improve the prospects for confirming (or otherwise) the hypothesis. The measurements comprise studies of the Cerenkov radiation from HEGRA (Arqueros et al., 1999), DICE (Kieda and Swordy, 1999) and CASA-BLANCA (Fortson et al., 1999) and a measurement of the important hadron component, from KASCADE (Horandel et al., 1999) plus an earlier measurement of hadrons which had not previously been examined from TIEN-SHAN (Adamov et al., 1990). We have already examined the HEGRA data, both Cherenkov and particles (Erlykin and Wolfendale, 1999b) but include the Cherenkov results again for completeness.

It is well known that, given an apparatus of adequate characteristics, the Cherenkov technique is a good one insofar as it integrates, to a large extent, the energy lost by the primary particle and thus gives the energy of the primary. Furthermore, from a determination of the depth of maximum of the shower, it enables an estimate to be made of the mass of the primary particle.

The extent to which energy-dependent systematic and random errors affect the large scale features of the Cherenkov-inferred energy spectra will be considered later. What should be seen, however, with reasonable precision, is ‘fine structure’ in the spectral shape.

Fig. 2 summarises the spectra derived by us from the 5 experiments referred to, and adjusted by us so that a comparison can be made. We have used a bin-width of $\Delta \log E = 0.2$ in our usual way. The ‘adjustment’ involves taking the main knee – which can be determined with reasonable accuracy in every case – as the datum for both energy and intensity. It is a well known feature of EAS measurements that, because of different biases, analysis procedures etc., the knee positions and intensities differ somewhat. The overall slopes of the spectra often differ, too, for reasons of different assumptions about the conversion from measured quantity to energy. Nevertheless, the shapes of the spectra in the region of the knee are usually reasonably stable.

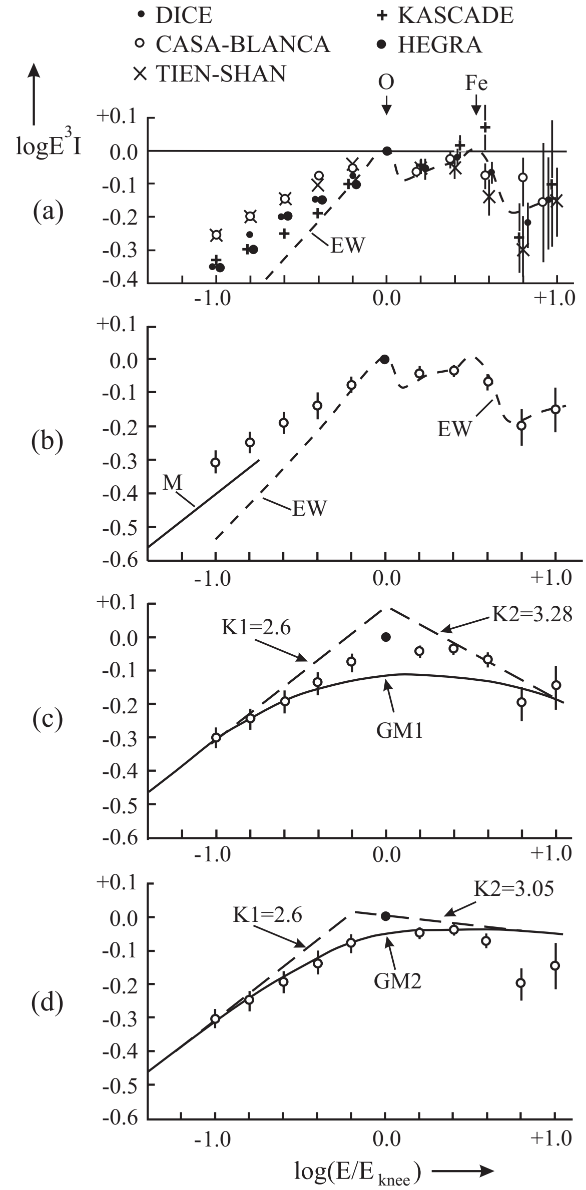

Fig. 2a–d. Combination of the very recent measurements of the cosmic ray spectrum (plus Tien-Shan). **a** Individual intensities plus our datum spectrum (Erlykin and Wolfendale, 1998a), denoted EW. All ‘intensities’ are displacements from the identified knee. **b** Averages of the intensities from **a** plus EW. It will be noted that, above the knee, the points are consistent with EW, whereas below they are not. **c**,**d** Attempts to fit the points with alternative versions of the Galactic Modulation Model – denoted GM1 and GM2. Neither fits, nor will any of this general smooth shape.

These features are apparent in Fig. 2. After the (first) knee – indicated O (Oxygen) – there is good consistency between the different sets of data. The mean values are close to our prediction (the EW dashed curve at the knee and beyond); the small residual differences can be easily explained in terms of uncertainties in energy estimation – these smooth out the peaks and troughs. In fact, even without smoothing, the fit of the mean points to the 'EW' prediction is quite good, the value of χ^2 divided by the number of degrees of freedom is χ^2/NDF = 0.5.

The situation *before* the knee (i.e. at lower energies) is more complicated. Firstly, the KASCADE and HEGRA intensities are lower than the others. It is possible that the problem lies in the conversion from measured signal, to primary energy, which is model dependent. It is interesting to note that the earlier Cherenkov results from TUNKA (Gress et al., 1999) and CACTI (Paling et al., 1997, Paling, 1997) are near to the KASCADE value. Secondly, the prediction from our model (EW) does not fit any of the points, the exponent of the energy spectrum ('gamma' in $E^{-\gamma}$) is too small. There are several possibilities to explain the discrepancy, as follows.

(i) EW may be correct and the fault lies with the Cherenkov results! It is not unlikely that the lowest energy points are too high here because of the effect of undoubted larger measurements errors for the faint Cherenkov light signal in the small showers measured. The lower intensities given by TUNKA and CACTI confirm the difficulty of making measurements in that energy region.

(ii) The EW spectral intensities may be too high at the knee energies, which gives the smaller slope below the knee when the spectrum is constrained by the results of direct measurements at $\sim 10^4$ GeV. Our model could the 'tuned' to fit – nothing done so far by us would be seriously affected because the majority of the analysis related to the knee region and log(E/E_{knee}) up to ~ 1.0 and beyond.

(iii) In fact, it is likely that the 'true' spectrum is in between EW and the points in Fig. 2b for the following reason. The most recent direct measurements at lower energy when extrapolated so that the line would reach the knee yield the line denoted M.

Comparison is made in Fig. 2(c) and 2(d) with what we expect from the conventional Galactic Modulation Model. These are denoted GM1 and GM2. The former normalises GM to the point of lowest energy and uses the 'standard' value of K_1 (= 2.6) below the knee. At the highest energies we use the mean of the measured intensities. The asymptotic slope above the knee, K_2 = 3.28, is chosen to give the virtual knee (intersection of the straight lines) at the 'correct' energy. The reduced chi-squared values are χ^2/N = 20.7 for GM1 and 5.3 for GM2. Both are impossibly bad. GM2 is an attempt to give the best fit to the points for the GM model. K_1 is chosen as before, K_2 (3.05) corresponds to the best estimate from measurements at energies higher than those shown here. Even here, the fit is impossibly bad.

3. Conclusions

We conclude that the claim for interesting structure in the cosmic ray energy spectrum in the range 1-10 PeV is strengthened. In addition to multiple electron and muon size spectra, the previous and new Cherenkov light measurements together with hadron size spectra now significantly complement and complete the sample of EAS particle components, where the fine structure around the knee is observed. Our Single Source Model is the most likely one that we can think of to explain the observed structure.

Acknowledgements. The authors thank The Royal Society for financial support and the Referee for helpful comments.

References

Adamov, D.S. et al. 1990, *Proc. 21st ICRC, Adelaide* **9** 260.
Arqueros, F. et al., 1999, *Astron. and Astrophys*. (in press).
Berezhko, E.G. et al., 1996, *JETP*, **82**, 1.
Erlykin, A.D. and Wolfendale, A.W., 1997a, *J. Phys. G* **23** 979; 1997b, *Astropart. Phys.* **7** 1; 1997c, *Astropart. Phys.* **7** 203; 1998a, *Astropart. Phys.* **8** 265; 1998b, *Astropart. Phys.* **9** 213; 1998c, *Astropart. Phys.* **9** 349; 1999a, *Astropart. Phys.* **10** 63; 1999b, *Astron. Astrophys.*, **350** L1.
Erlykin, A.D., Lipski, M. and Wolfendale, A.W., 1998, *Astropart. Phys.* **8** 283.
Fortson, L.F. et al., 1999, *Proc. 26th ICRC* **3** 125.
Gress, O.A. et al., 1999, *Nucl. Phys. B (Proc. Suppl.)* **75A** 299.
Horandel, J.R. et al., 1999, *Proc. 26th ICRC* **1** 337.
Kieda, D.B. and Swordy, S.P., 1999, *Proc. 26th ICRC* **3** 191.
Osborne, J.L., Wolfendale, A.W. and Zhang, L., 1995, *J. Phys. G.* **21** 429 and references therein.
Paling, S. et al., 1997, *Proc. 25th ICRC* **5** 253.
Paling, S., 1997, Ph.D. thesis, University of Leeds, UK.