Single Source Model of the Knee: Present Status

A.D.Erlykin[1], **and A.W.Wolfendale**[2]
[1]*P.N.Lebedev Physical Institute, Leninsky pr. 53, Moscow 117924, Russia*
[2]*Physics Department, University of Durham, Durham DH1 3LE, UK*

Abstract

New data available since our last publication have been analysed from the standpoint of checking our hypothesis. These comprise more EAS size spectra (almost a doubling of the number), new Cherenkov light spectra and more muon data. The muon information includes multiple muons of high energy detected underground. All the data confirm our hypothesis that there is 'structure' in the primary spectrum which cannot be explained by the conventional model.

1 Introduction:

During the last two years we have examined the world's data on EAS and demonstrated that there is structure in the knee region of the corresponding primary spectrum ($E_0 \approx 3$ PeV) which cannot be explained by the conventional Galactic diffusion model (see, e.g. Erlykin & Wolfendale, 1998, denoted EW, 1998). From the beginning (EW, 1997) we have favoured a specific model involving the *explosion of a single, nearby and recent supernova*. It is proposed that that this supernova exploded some few tens of thousands of years ago and was not further than 100 - 200 pc from the solar system. In this model acceleration of particles by the supernova shock occured in the hot interstellar medium of the Local Bubble, surrounding the solar system.

Our earlier analysis of experimental data was based on a sample of 16 different EAS size spectra, but, since 1997, the number of available spectra has nearly doubled and now stands at 31. The new arrays, CASA-MIA and KASCADE, have started to provide data of very high statistical precision (although, alas, most of it is for large slant depths in the atmosphere). Furthermore, the number of available EAS muon size spectra has increased from 4 to 10 and they are also included in the analysis. The number of Cherenkov light spectra has doubled, from 2 to 4. Here we present the results of the analysis made with the updated sample of spectra.

2 EAS electron size spectra

The bulk of the new data has come from CASA-MIA (7) (Glassmacher et al.); KASCADE (5) (Glasstetter et al.); Akeno (3) (Nagano et al.); and the rest - from Chacaltaya SYS (Honda et al.); KGF (Acharya et al.); and Baksan (Chudakov et al.,1997) (the number in parentheses represent the number of constituent spectra - at different zenith angles). As in our previous analysis we determined the position of the knee as the point of the maximum curvature or the maximum sharpness of the spectrum ('sharpness' being the second differential of the *log intensity* versus *log size*; the bin size is $\Delta log N_e = 0.2$). The entire set of these data shows a clear trend of decreasing $log N_e^{knee}$ and knee sharpness with increasing atmospheric depth, in agreement with expectation. Figure 1 shows the results for all the available data (not just the new results). As is not uncommon, the spread of points about the lines (full -

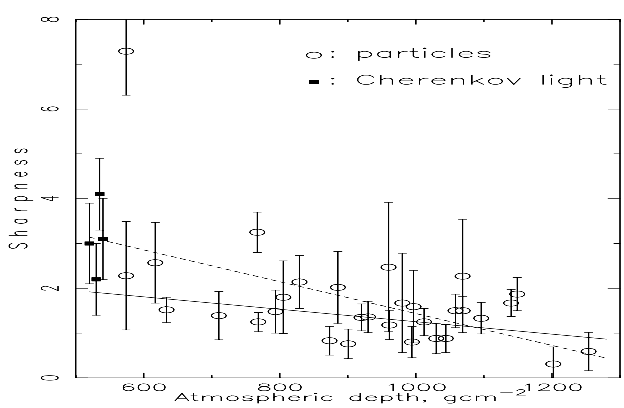

Figure 1: Sharpness of the knee from all available EAS experiments as a function of atmospheric depth. The lines are simply best fit lines to the data. Also shown are Cherenkov results (solid 'squares') not used in the fit (see section 5 of this paper)

weighted and dashed - unweighted) is greater than expected from the indicated errors on the points themselves. This means that there are additional errors, not included. The result is that the correct best-fit line is presumably somewhere between the two lines drawn in the Figure. In any event, there is a clear systematic dependence, in the expected direction.

In principle, the sharpness in the primary spectrum itself (denoted S$_p$) can be derived from this plot since the effect of development fluctuations is understood and allowance can be made for the finite bin-size over which the sharpness values are determined. The result is S$_p$ $\sim$ 5 when the bin-size alone is corrected for. If the σ-value for the $logE_0$ resolution is 0.2, this converts to S$_p$ $\sim$ 20 for zero resolution. Without any doubt, S$_p$ is very much bigger than the maximum ($\simeq$ 0.3 - see EW, 1998) for a conventional Galactic modulation model with a mixed mass composition.

Concerning the important 'iron peak', insofar as many of the new experiments do not extend far enough in shower size, progress has been less. Nevertheless, the results are consistent with those for the knee and the estimated sharpness in the primary spectrum.

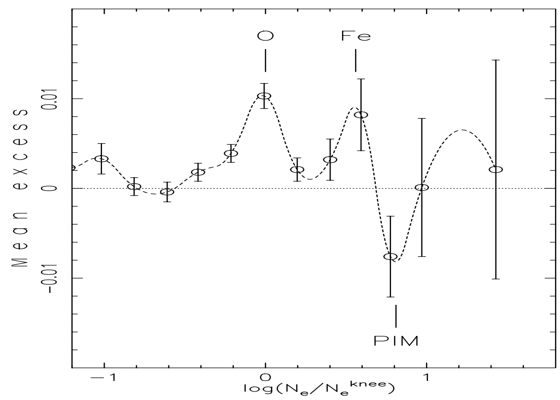

Figure 2: Excess over the running mean. Three important features are shown: the O-peak, the Fe-peak and the post-iron minimum, (PIM).

Another way of studying the 'peaks' is to examine the individual points with respect to their local running mean. Figure 2 shows the results. *All the characteristic features of the spectra* which have been found in the previous analysis and were the basis for our model: the intensity peaks at the knee ('oxygen'), at $log(N_e/N_e^{knee}) = 0.56$ ('iron') and the post-iron minimum, *are confirmed with the better statistics.* The peak heights are somewhat smaller than our previous average (EW, 1998) - an understandable result in view of the inclusion now of the larger depth - smaller sharpness - values.

3 EAS muon size spectra

Insofar as (energetic) muons are intimately concerned with the early interactions of the primary particles they should give useful information on the structure in the primary spectrum. The drawback is that only several percent of EAS secondaries at ground level are muons and statistical fluctuations can be serious.

In new work (EW, 1999) we have analysed all the available muon spectra (in this case using a bin size $\Delta logN_\mu = 0.1$). Two salient effects appear: (a) the spread of intensities above the knee are less than for electrons, and the knee position varies with depth more smoothly, too; (b) the position of the knee, $logN_\mu^{knee}$, decreases and the sharpness of the knee increases with increasing muon threshold energy. Figure 3 shows the situation for sharpness. The results for the iron peak, which are necessarily imprecise, are also given.

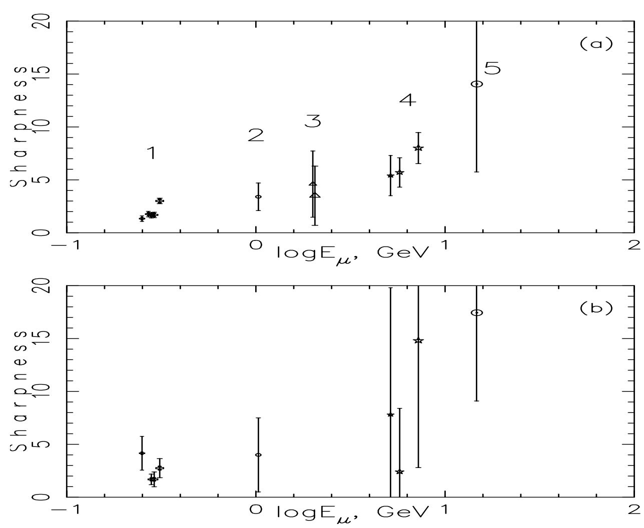

Figure 3: Sharpness of the knee in the muon size spectrum as a function of muon threshold energy, (a); that for the 'iron-peak' is also given, (b). Sources of data: 1.KASCADE (0.25 GeV); 2.EAS-TOP; 3.KASCADE(2 GeV); 4.Tien-Shan-EAS; 5.Ohya.

The high values and a general increase of the sharpness with threshold energy can be understood in terms of a closer approach to the upper part of cascade development, which is better connected with the primary energy. However the values for the 'truncated-muons' from the KASCADE experiment (Haungs et al.) with $E_\mu > 0.25$ GeV, seem too low.

As shown in Figure 4, the separation between the knee and the iron peak $log(N_\mu^{Fe}/N_\mu^{O})$ is clearly less for truncated muon size spectra, than for total muon size spectra. Taking into account that the truncated muon size does not depend on the primary mass, the larger separation for the peaks in the total muon size spectra can be understood only if the mean primary mass in the iron peak is heavier than in the knee. *That gives additional support for our model*.

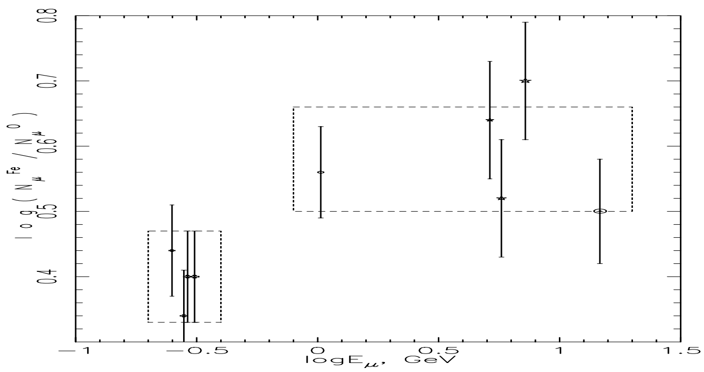

Figure 4: The separation between the knee and the iron peak. Left group of points is for truncated muon size spectra used by KASCADE, right points are for the total muon size spectra.

4 Multiple muons

Measurements of multiple muons have been made by a number of large underground detectors and these bracket the energy region of the knee (but not, yet, the iron-peak). Inspection of the results from MACRO (Ambrosio et al.), Baksan (Chudakov et al.,1991) and Frejus (Berger et al.), which relate to muon threshold energies in the range 1.2 - 3.2 TeV, all show evidence for sharp irregularities at roughly consistent (inferred) primary energies. The results for MACRO and Baksan for a muon energy of 1.3 TeV have been examined in detail. The values, S $\approx$ 4 for MACRO (Δlog(m) = 0.1), and S $\approx$ 10 and 2.9 for Baksan (Δlog(m) = 0.1 and 0.2 respectively), for example, are just what we expect, i.e.'high' because they relate to very early interactions. Figure 5 shows the results for MACRO and Baksan; the inferred distribution of <u>mean</u> multiplicity (dashed curve) has been derived by us assuming that the fluctuations are purely Poissonian; we consider that this is the case because they arise mainly from the $\pi - \mu$ decay probability distribution. The other multiple muon data from Baksan with muon energy thresholds of 2.0 and 3.2 TeV, also data from Frejus, give similar results but detailed analysis is still proceeding.

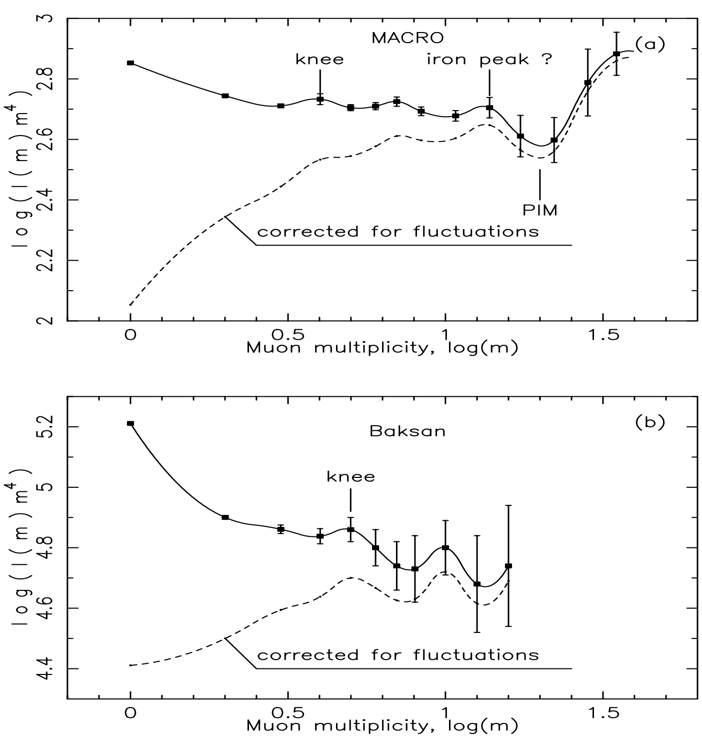

Figure 5: Multiple muons from the MACRO (a) and Baksan (b) experiments. Points and full curves - experimental data, dashed curves - spectra corrected for fluctuations estimated by us from the data. Positions of the expected knee, iron peak and post-iron minimum are indicated (the 'knee' is at the intersection point of straight lines, and is also roughly where expected from our model calculations).

5 Cherenkov light results

As is well known, Cherenkov light measurements should give rather precise indications of the primary energy spectrum, statistical errors permitting. The contemporary data available are given in Figure 6. No normalization of knee position has proved necessary, unlike in our earlier analysis (EW, 1998), where the HEGRA measurements gave a knee position of 2 PeV, a value significantly below our preferred value. We commented then that the value was too low and this has recently shown to be the case (Arqueros et al.); i.e. the knee is now at 4 PeV,(+4.6,-0.8 PeV)

Continuing with remarks about the HEGRA spectrum we have taken the actual Cherenkov light results and it is these which are presented in Figure 5. The sharpness (with $\Delta log E = 0.2$) for all the data is 3.0 $\pm$ 1.0. It is this value that is plotted in Figure 1 at an atmospheric depth of about 550 g$\cdot$cm^{-2} (i.e. near shower maximum). It is remarkable that in spite of a minor difference in the individual positions of the knee the sequence of peaks in *all spectra* beyond the knee is just what we predicted from our model (full line denoted E&W).

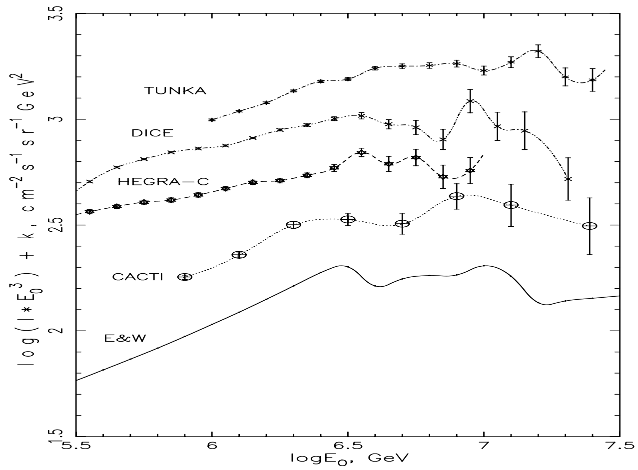

Figure 6: Cherenkov light data: Tunka from EW, 1998 (k=0.6), DICE from Boothby et al. (k=0.5), CACTI from Hillas (k=-0.1), HEGRA from Arqueros et al.(k=0) as described in the text. E&W - prediction of our model (k=-0.5).

6 Conclusion

New data, an extended sample of EAS electron size spectra, low energy EAS muon size spectra, high energy muon multiplicity spectra and new Cherenkov light measurements, all confirm our claim that there is 'structure' in the primary energy spectrum, the sharpness of which cannot be explained by the conventional model. A remarkable sequence of irregularities, which we associate with O, H and Fe components in the single source, as well as the post-iron minimum, are observed in all the major EAS components.

References

Acharya, B.S. et al. 1985, 19th ICRC, La Jolla 2, 226

Ambrosio, M. et al., 1997, Phys. Rev. D56, 1407; 1418

Arqueros, F., et al., 1999, A&A (in press)

Berger, Ch. et al., 1989, Phys. Rev. D40, 2163

Boothby, K. et al., 1997, ApJ. Lett., 491, L35; 1997, Nucl.Phys.B (Proc.Suppl.), 52B, 166

Chudakov, A.E. et al. 1991, 22nd ICRC, Dublin 2, 5

Chudakov, A.E. et al. 1997, 25th ICRC, Durban 6, 177

Erlykin, A.D. & Wolfendale, A.W. 1997, J.Phys.G: Nucl.Part.Phys. 23, 979

Erlykin, A.D. & Wolfendale, A.W. 1998, Astrop. Phys. 8, 265

Erlykin, A.D. & Wolfendale, A.W. 1999, to be submitted

Glassmacher, M.A.K. et al. 1999, Astrop. Phys. 10, 291

Glasstetter, R & Hörandel, J.R. 1998, Rayos Cósmicos 98, 16th ECRC, Alcala, 563

Haungs, A. et al. 1999, Forsch. Karlsruhe FZKA 6263

Hillas, A.M. 1998, Vulcano Workshop 'Frontier Objects in Astrophysics and Particle Physics' (in press)

Honda, K. et al. Nucl.Phys.B (Proc.Suppl.) 1999 (in press)

Nagano M. et al. 1984, J. Phys.G: Nucl. Part. Phys. 10, 1295 & priv. comm.