April, 28, 1999

MUONS AS AN AID TO ANSWERING THE QUESTION: WHAT IS THE ORIGIN OF THE COSMIC RAY KNEE ?

[1] A.D. Erlykin [(1)], A.W.Wolfendale [(2)]

(1) P. N. Lebedev Physical Institute - Moscow, Russia

(2) Department of Physics, University of Durham, Durham, UK

Abstract

The Single Source Model of the knee, developed by us on the basis of a world survey of EAS data, also makes certain predictions for cosmic rays of lower, sub-PeV energies. This energy region is of special interest for the CosmoLep experiment. The feasibility of the ALEPH detector to study muons in this energy region, and prove or disprove our model predictions, is discussed.

A brief survey is made of relevant muon data from the (few) experiments carried out so far (Fig.1).

1 The Sharp Knee

One of the most remarkable features of the 'knee' in the size spectrum of cosmic ray showers, which helped it to be discovered, is its sharpness. The EAS size spectrum changes its slope by ~ 0.5 in $logN_e$-interval less than 0.5 [1], which immediately leads to the conclusion that the sharpness, defined as the first derivative of the slope or the second derivative of intensity: $\chi = -\frac{d^2(logI)}{d(logN_e)^2}$ is bigger than 1. When the role of fluctuations in the development of EAS is realised [2], it becomes clear that the sharpness in the primary energy spectrum must be bigger still. This feature has puzzled the cosmic ray community for decades, because the sharpness expected for the most popular model of the knee, the diffusion model, taken with a mixed primary mass composition, does not exceed 0.3.

[1]E-mail address: A.D.Erlykin@durham.ac.uk

2 The Single Source Model of the Knee: an update.

During the last 2 years we have developed a model of the knee which explains the remakable sharpness and other features observed in cosmic rays near the knee [3, 4, 5, 6, 7, 8, 9, 10]. The basic conclusion of this model is that the knee is due to the *explosion of a single, nearby and recent supernova.* This supernova exploded some few tens thousands of years ago and was not further than 100 - 200 pc from the solar system. The acceleration of particles by the supernova shock occured in the hot interstellar medium of the Local Bubble, surrounding the solar system.

The energy spectrum of accelerated particles that we have adopted has been taken from the model of supernova shock acceleration developed by Berezhko et al. [11] (Fig.2a,b). His model gives a 'flat' energy spectrum below the knee (E^{-2}), a high maximum energy of the acceleration process and very sharp cut-off of the spectrum beyond this maximum energy. It is the sharp cut-off when applied to the single supernova that gives birth to the sharp knee.

The mass composition of the accelerated particles has been obtained by fitting the observed structure of the EAS size spectra near the knee. It is shown in Fig.2c,d. Our earlier fitting and analysis were 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 spectra. The new arrays, CASA-MIA and KASCADE have started to provide data of very high statistical precision. 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 Ĉerenkov light spectra has also doubled, from 2 to 4. New data on the EAS hadron size spectra have also appeared. All these new sets of data give additional support to our claim that the knee in the primary energy spectrum is sharp and that there is a second irregularity at a primary energy higher than the energy of the knee by a factor of 3.5-4, i.e. at about 10-12 PeV.

2.1 EAS Muon Size Spectra and their Characteristics

Because the first measurements, devoted to the cosmic ray study at ALEPH and L3, were made of the muon multiplicity spectrum, it might be interesting to look at muon size or muon multiplicity spectra made by other experiments at other muon and primary energies. In fact, the muon multiplicity spectrum measured by LEP detectors is the muon density spectrum for muons of relatively high (tens of GeV) threshold energy. The density spectrum is the derivative of the muon size spectum and when all muon sizes and EAS core distances contribute to the observed muon density. Fig.3 presents the available muon size spectra.

The KASCADE spectra were given for the so called *truncated* muon size N_μ^{tr}, which contains only muons between 40 and 200 m from the shower axis. In order to compare them with the other spectra, which used the total muon size, N_μ, we converted N_μ^{tr} to N_μ multiplying them by 3.4 [12] (Fig.3a). Total muon size spectra, measured by EAS-TOP, Tien-Shan EAS and Ohya are shown in Fig.3b (see references in [6]). Short vertical lines in Fig.3 indicate the position of the knee, determined as the point of maximum curvature.

The next point with a maximum curvature to the right of the knee determines the position of the second peak. It is separated from the knee by $\Delta(logN_\mu) \approx 0.41$ for truncated muon size spectra measured by KASCADE (Fig.4a) and by $\sim 0.51-0.53$ for the total muon size spectra measured by other arrays (Fig.4b). The difference in the separation as the function of the muon threshold energy is more clearly seen in Fig.5, but we think that it is not due to the muon energy but due to the difference in the primary mass dependence for the truncated muon size in KASCADE and the total muon size in EAS-TOP, Tien-Shan EAS and Ohya. Because the truncated muon size in KASCADE is independent of the primary mass, the larger separation of the second peak from the knee for the total muon size spectra can be understood if the mean primary mass in the second peak is greater than in the knee (Fig.6). We called it *the iron peak*.

The knee is also seen in the muon density spectra if measured at fixed distances from the EAS core. The muon density spectra for > 2 GeV muons, measured by KASCADE [13] and processed by us to determine the position of the knee are shown in Fig.7. The same spectra normalized at the knee position are shown in Fig.8.

Fig.9 shows the positions of the knee and the iron peak as the function of the muon threshold energy. The regular decrease of both positions with rising E_μ is seen and gives the credit to the results of our processing. Full lines in this figure show the expected energy muon spectrum $N_\mu(> E_\mu)$ for 3 PeV oxygen induced showers (the knee) and for 10 PeV iron induced showers (the iron peak), calculated using CORSIKA + QGSJET. The agreement with an expectation from our SS model is quite good.

There is also an indication of a regular behaviour of the sharpness in the knee and in the iron peak when plotted as a function of the muon threshold energy; as Fig.10 shows, there is a tendency of the sharpness to rise with rising muon energy both for the knee and for the iron peak. The sharp knee is also observed in the muon density spectrum [13]. The corresponding point for $E_\mu > 2$ GeV is shown in Fig.9a and 10a.

At much higher muon energies the situation should be different. Larger fluctuations, intrinsic for the muon production at the highest energies, should smear out the sharp knee and eventually reverse the tendency, seen in Fig.10, for the sharpness to rise with muon energy. Indeed the the multiplicity spectrum of muons with $E_\mu > 1300$ GeV, measured by MACRO [14] is substantially steeper with a differential slope of about 4 (Fig.11). However the traces of knee and of the iron peak still remain; in fact, they are precisely at the right place, expected from the value of the integral intensity. Even the sharpness of the irregularity seen at the expected position of the knee is about 4.1 ± 0.3, which is quite high.

An attempt has been made by us to correct for fluctuations, with the (approximate) result, shown dashed, in Fig.11. The knee reappears rather strongly. The dip after the 'iron peak' reported by us [6] is seen rather well, here too.

The integral intensities above the knee, though having a large spread, are consistent with the integral intensities derived using the same technique from electron size spectra, measured by the same arrays (Fig.12). It gives support to the astrophysical origin of the knee.

3 Below the Knee

The result of averaging all the available EAS intensities above the knee, is:

$$\langle logI(> N_{e,\mu}^{knee}) \rangle = -10.77 \pm 0.14 cm^{-2}s^{-1}sr^{-1} \quad (1)$$

The corresponding intensity of EAS cores above the knee for ALEPH is only about one per 100 run hours. Such a value is not enough for the study of the knee region, particularly in view of the limited life time of the CosmoLep experiment before the final shut-down of LEP in the year 2000. Actually the collecting area of ALEPH detector is larger than 16 m^2 of its TPC, but it is not very promising approach to study high energy showers by observing their periphery.

It is below the knee, however, where the rates are, of course, higher, that the ALEPH detector could be of considerable value for cosmic ray studies. The SS model gives predictions for this sub-PeV region, as follows (Fig.13):

1. The primary energy spectrum in the region 10 - 1000 TeV should have a concave shape. This feature is a consequence of the onset of the flatter SS spectrum with a differential slope index of 2 against the steeper background spectrum with a slope index about 2.7.

2. The mass composition of primary cosmic rays should become heavier with rising energy. This feature is a consequence of the rising contribution of SS, which provides predominantly M,H and VH groups of nuclei.

3. We have made a case for there being a small irregularity in the primary energy spectrum, and in the mass composition, which is due to $\sim$20% admixture of protons and/or helium nuclei in the SS [10]. Just as with the other SS components, protons should have a flatter spectrum and a sharp cut-off, in this case at about 440 TeV. These two features create a small mini-bump in the total energy spectrum, which should be visible in precise measurements. The demonstration of this mini-bump would be of considerable importance for the model.

4 A Study of Muons in the Sub-PeV Region

4.1 Single Muons

In general all the features listed above could be studied by high energy muons. As for the characteristics of single muons, they might be a powerful tool for the study of the sub-PeV region. It is a generally accepted convention that single muon characteristics are connected and reflect the characteristics of the primary nucleon spectrum. In our SS model the primary nucleon spectrum carries all the features predicted for the sub-PeV region: a concave shape, rising neutron to proton ratio and an irregularity at about 400-500 TeV/nucleon (Fig.14). Thus, the study of such characteristics as the momentum spectrum, the zenith angle distribution and the charge ratio of single muons might prove or disprove our predictions. However, the requirements for the relevant detector and the statistical accuracy of its data would need to be extremely high. It is known from calculations of the muon response function [15, 16] that the median energy of nucleons responsible for the production of single muons is only 7 times higher, and the mean nucleon energy only 14 times higher, than the energy of the muon. So, in order to find the irregularity at 400-500 TeV in the primary nucleon spectrum, the detector should be sensitive to muons of several tens of TeV.

It seems that the ALEPH detector with its maximum detectable momentum (m.d.m.) of about 0.2-0.3 TeV/c is unable to use single muons for such a study. However, L3+Cosmics, with its larger sensitive area and higher m.d.m. exceeding 1 TeV/c, has a better opportunity [17].

Irrespective of the particular predictions, our demonstration of 'structure' in the energy spectrum of primaries in the PeV region proves the value of a search for similar structures in the muon momentum spectrum and their charge ratio at *all* energies. It is relevant to point out that there are astrophysical possibilities at virtually all energies if sufficiently precise observations can be made.

4.2 Muon Families

Multiple muons are produced by primary cosmic rays of higher energies than single muons. The higher the muon multiplicity the higher is the mean primary energy responsible for the creation of such a muon group. Giant underground detectors such as the Baksan Underground Scintillation Telescope (BUST), MACRO and LVD [14, 18, 19, 20] have proved their potential ability to study sub-PeV and even PeV energy region (as we demonstrated in Fig.11 for MACRO). However, the CERN detectors, such as ALEPH and L3, have an important advantage compared with the Gran Sasso detectors: they have powerful magnets and can measure muon charge and momenta. By this way they are able to study the so-called *muon families*.

We introduced this term in [21] following an analogy with gamma- and hadron families, studied by X-ray emulsion chambers, and to distinguish them from the more traditional: *muon groups*. Both are actually the same phenomenon - the cores of EAS - seen by high energy muons. In contrast with gamma- and hadron families, collected from relatively low altitudes, high energy muons are collected from the upper part of the atmosphere. They have a much larger lateral spread and can be studied only by detectors of large sensitive area, such as BUST, MACRO and LVD. However, these detectors are situated deep underground and have information only on the muon threshold energy on the ground surface above the detector and the muon coordinates. In some rare cases they can estimate the minimum energy of an individual muon by measuring the energy of the cascade produced by this muon in the detector or in the surrounding rock. Unfortunately, the probability of these events is low and the efficiency of such measurements is correspondingly small.

The CERN detectors not only have sufficient area to collect many high energy muons in the shower, but they are also able to measure the individual energy of each muon in the group. The knowledge of individual muon energies in the family gives an opportunity to study the two-dimensional energy-lateral distribution of the muons in the shower core (Fig.15):

$$\frac{d^3W}{d\rho_\mu 2\pi R_\mu dR_\mu dE_\mu}(\rho_\mu, R_\mu, E_\mu) \qquad (2)$$

Here ρ_μ is the muon density, R_μ is the distance of the muon from the shower axis and E_μ is the muon energy. If there is no independent information on the position of the shower axis the distance R_μ can be measured from the baricenter of the family.

As a result of the unique knowledge of muon energies a few novel parameters can be used for the classification and for the study of muon families:

$$\sum_i E^i(> E_\mu) \qquad \sum_i E^i_\mu R^i_\mu(E_\mu) \qquad \frac{dW}{d(E^i_\mu R^i_\mu)}(E^i_\mu, R^i_\mu)$$

$$\overline{E_\mu R_\mu} \qquad \frac{dW}{dZ}(Z, E_\mu) \qquad Z = \sum_{ij} \frac{E^i_\mu E^j_\mu R^{ij}_\mu}{E^i_\mu + E^j_\mu}$$

where R^{ij}_μ is the distance between muons i and j. All of them could be included in a multidimensional non-parametric analysis to estimate the energy and the mass of the primary particle which produced the family [22]. Energy-lateral characteristics of muon families could be used also for the study of the transverse momenta of secondaries and the scaling properties of their energy spectra [21].

As for the use of a more traditional approach, the muon multiplicity spectra and the fluctuations of the muon density could be studied above the different muon energy thresholds, increasing by this way the credibility of the relevant conclusions [21]

5 Structure Analysis

Another important facility provided by the large area magnetic spectrographs, such as ALEPH and L3, is the possibility of studying the structure of the 'target diagram', i.e the two-dimensional picture of the muon family. Such an approach has been successfully used in emulsion chambers [23] and has started to be used for muon groups [24, 25] This study gives an opportunity to reveal possible asymmetries in the muon azimuthal and azimuth-charge distributions, to find traces of clustering and jets in the production of secondary particles, consequence of the possible QGP formation [26], 'sling effects' [27, 28] and so on (Fig.16). The advantage of the muon families compared with the gamma- and hadron ones is that muons are collected from much higher altitudes; hence, they are more sensitive to the initial stages of cascade development and might preserve the information on some characteristics of the primary interactions.

6 The Desirability of a Ground-based Array

In the present version of the ALEPH and L3+Cosmics experiments the information on muon families is largely integrated over the whole range of EAS core distances and primary energies. To increase the information and sensitivity of the experiments to the underlying physics of the primary particles and their interactions it would be extremely useful to have a ground based array above the underground detectors (Fig.17).

7 Conclusion

The motivation outlined above demonstrates that the problems of sub-PeV cosmic ray physics, promised by the large area LEP detectors, ALEPH and L3, are very rich and important. The best way farward appears to be a study of muon families by the multi-dimensional non-parametric method with the use of the structure analysis. Such an approach would answer the following questions:

(i) Is there structure in the primary energy spectrum in the energy range up to some tens of TeV/nucleon (the use of single muons) ? Similarly, is there structure in the mass spectrum ?

(ii) Is there support for our contention that the primary energy spectrum is concave before the PeV region ? Similarly, does the mean mass increase (the use of muon families) ?

(iii) Is there evidence for interesting new interaction phenomena in the early primary interactions (the highest energy muons, both singly and in families) ? (Fig.18).

Captions to Figures

Figure 1. Contents of the talk.

Figure 2. Primary cosmic ray energy spectrum in SS model: (a) structure of the background; (b) structure of the single SNR spectrum; (c) primary mass composition; (d) $< lnA >$ - mean primary mass parameter.

Figure 3. EAS muon size spectra: (a) measured at KASCADE (K(l) = 0) for *truncated* muon size and zenith angle intervals (from top down): $0° - 18°$, $18° - 24.9°$, $24.9° - 30°$, $30° - 34°$, $34° - 37.3°$. The total muon size was derived from the truncated size multiplying the latter by 3.4 [12]. (b) measured at EAS-TOP (K(l) = -1), Tien-Shan EAS (K(l) = 0) for zenith angles (from top down) $0° - 20°$, $20° - 40°$, $40° - 60°$ and Ohya (K(l) = 0). Short vertical lines indicate positions of the knee, determined by the maximum curvature method. Straight dashed lines indicate the weighted fit of the spectra by a power law below and beyond the knee.

Figure 4. The same muon size spectra as in Fig.3, normalized at the position of

the knee. The mean position of the second peak is indicated by the dashed vertical line at $log(N_\mu/N_\mu^{knee} \approx 0.41$ for truncated muon size spectra (a) and by the dotted line at $\sim 0.51 - 0.53$ for the total muon size spectra (b).

Figure 5. Separation of the iron and the knee (oxygen peak) as the function of the muon threshold energy.

Figure 6. An explanation of the difference in the separation between the second peak and the knee for truncated and total muon size spectra as due to the greater mean primary mass in the second (iron) peak.

Figure 7. (a) Muon density spectrum at two distances from the EAS axis in KASCADE for muons with the energy above 2 GeV. Short vertical lines indicate the position of the knee determined by us.

(b) Sharpness of the muon density spectra in KASCADE.

Figure 8. Muon density spectra in KASCADE normalized at the position of the knee.

Figure 9. Position of the knee (a) and the iron peak (b) as a function of the muon threshold energy. The position of the knee in KASCADE, measured for *truncated* muon size spectra, is moved upwards by log(3.4), to convert it to the equvalent position for the total muon size spectra. For the iron peak, the upward displacement is a little bigger (log(3.85)). The full lines are the expected dependence for oxygen and iron induced showers calculated using the QGSJET model. Small and large open triangles at $logE_\mu \approx 0.3$ in (a) mark the knee positions derived from the muon density spectrum at 40 - 45 m and 65 - 70 m from the shower core respectively [13].

Tigure 10. The sharpness of the knee (a) and of the iron peak (b) as the function of the muon threshold energy. Small and large open triangles at $logE_\mu \approx 0.3$ in (a) mark the sharpness derived from the muon density spectrum at 40 - 45 m and 65 - 70 m from the shower core respectively [13].

Figure 11. Muon multiplicity spectrum at MACRO [14]. The data have been combined by us to give intensities equally spaced in *log(m)* for $m > 5$. Expected knee and iron peak positions are indicated. Dashed line is the muon multiplicity spectrum expected if fluctuations are negligibly small. Dash-dotted line shows the shape of the multiplicity spectrum, expected from our SSM, the curve is normalized

to the experimental knee position.

Tigure 12. The consistency of the integral intensities above the knee and the iron peak in the muon (a,b) and electron (c,d) size spectra for the same EAS arrays.

Figure 13. SS model predictions for the primary energy region below the knee.

Figure 14. Structure of the primary energy spectrum (a) and primary nucleon spectrum (b) in SS model.

Figure 15. Basic characteristics of muon families, which could be studied at ALEPH and L3+Cosmics.

Figure 16. Illustration of the structure analysis for the muon families.

Figure 17. Desirability of the ground-based array - the principal possibility to estimate the primary mass and the primary energy of the particle creating a muon family.

Figure 18. Conclusion of the talk.

References

[1] Kulikov G.V., Khristiansen G.B. 1958, JETP, **35**, 635

[2] Zatsepin G.T. 6th ICRC, Moscow, 1959, **2**, 192

[3] Erlykin A.D., Wolfendale A.W. J.Phys.G: Nucl.Part.Phys. 1997, **23**, 979

[4] Erlykin A.D., Wolfendale A.W. Astropart. Phys. 1997, **7**, 1

[5] Erlykin A.D., Wolfendale A.W. Astropart. Phys. 1997, **7**, 203

[6] Erlykin A.D., Wolfendale A.W. Astropart. Phys. 1998, **8**, 265

[7] Erlykin A.D., Lipski M., Wolfendale A.W. Astropart. Phys. 1998, **8**, 283

[8] Erlykin A.D., Wolfendale A.W. Astropart. Phys. 1998, **9**, 213

[9] Erlykin A.D., Wolfendale A.W. Astropart. Phys. 1998, **9**, 349

[10] Erlykin A.D., Wolfendale A.W. Astropart. Phys. 1999, **10**, 69

[11] Berezhko E.G. et al. JETP, 1996, **82**, 1

[12] Roth M. PhD thesis, Univ. of Tübingen, 1999

[13] Haungs A. et al. Wissenschaftliche Berichte, FZKA 6263 and these Proceedings.

[14] Ambrosio M. et al.(MACRO coll.) Phys.Rev. 1997, **D56**, 1407

[15] Erlykin A.D., Ng L.K., Wolfendale A.W. J.Phys.A, 1975, **7**, 2074

[16] Gaisser T.K. 13th ICRC. Denver,1973, **3**, 1860

[17] Le Coultre P. et al. (L3+Cosmics group), 25th ICRC, Durban, 1997, **7**, 305

[18] Voevodsky A.V. et al. Izv. RAN, ser.fiz., 1994, **58**, 127

[19] Bakatanov V.N. et al. Astropart. Phys. 1997, **8**, 59

[20] Aglietta M. et al. (LVD coll.) Astropart. Phys. 1998, **9**, 185

[21] Danilova T.V., Erlykin A.D., Procureur J. J.Phys.G: Nucl.Part.Phys. 1989, **15**, 509

[22] Chilingarian A.A. Nucl.Instr. and Meth., 1989, **A281**, 388; Nuovo Cim. 1991, **14C**, 555

[23] Borisov A.S. et al. 25th ICRC, Durban, 1997, **6**, 61

[24] Battistoni G. 24th ICRC, Rome, 1995, **1**, 508

[25] Scapparone E. Vulcano Workshop 1996, Frontier Objects in Astrophysics and Particle Physics, Conf. Proc. **56**, 455

[26] Schukraft J. Nucl. Phys.B (Proc. Suppl), 1999 (to be published)

[27] Dremin I.M., Man'ko V.I. Nuovo Cim., 1998, **111A**, 439

[28] Erlykin A.D., Wolfendale A.W. Nucl. Phys.B (Proc. Suppl), 1999 (to be published)