The Cosmic-Ray Knee: Still a Mystery

Frank C. Jones, Robert Streitmatter and Demosthenes Kazanas
Laboratory for High Energy Astrophysics
NASA/Goddard Space Flight Center
Greenbelt, MD 20771
USA

Abstract

There are several questions concerning the cosmic-ray knee. The first concerns its sharpness. Recent measurements estimate that it takes only about a half decade in energy to fully transit the knee while almost all propagation models require nearly two decades to accomplish this. The second is the general tendency of the composition to trend towards protons as the knee is approached from below and then abruptly trend toward a heavier composition upon crossing the knee. We have proposed a two-component source model combined with the onset of a new interaction at 3×10^{15} ev which explains these phenomena. However, data from HiRes indicate a trend back towards protons at yet higher energy which our model cannot explain without extension. Furthermore, if the HiRes data turns out to show the GZK cutoff at the expected energy it will demonstrate that there is either no energy-losing interaction taking place or that it has become insignificant at these energies. Finally, we note here that an explanation of the knee as the successive loss of particles of increasingly higher Z has serious problems as well.

1. Introduction

In a previous paper [8] we discussed the possibility that the observed [4] composition lightening of the cosmic ray spectrum approaching the knee from low energy could be caused by a source of protons with a spectral index somewhat harder than the bulk of the cosmic rays. In addition we proposed [9] the possibility that the knee itself was produced by the onset of new physics of proton interactions at energies $> 3 \times 10^{15}$ ev. Employing Heitler's [6] "Toy Model" of air showers we have investigated the effect of this additional, harder proton spectrum in combination with the altered interaction.

2. The Toy Model

Consider two types of products from a hadron collision, "A" type particles that interact (producing more hadrons) and "B" type particles that don't (thus

pp. 271–274

carrying away "lost" energy).

Assume that in each collision there are α A-type particles and β B-type particles produced as long as the energy of the incoming particle is above a critical energy E_c. Further consider that in each collision all of the incoming energy is shared equally among the $\alpha + \beta$ produced particles. The energy going into B type particles is lost. So, after the first collision the lost energy is $E_{L1} = E_0\beta/(\alpha + \beta)$, the energy remaining for the second interaction level in the chain is $E_{R1} = E_0\alpha/(\alpha + \beta)$, and after N collision levels the total amount of energy lost to the process is just the sum of the energy lost at each level $E_{LN} = E_0(1 - (\alpha/(\alpha + \beta))^N)$.

When the energy per particle drops below E_c subsequent interactions can not produce a B-type particle. Thus there will be a number of shower generations, N_c, after which the shower will develop normally. $N_c = (\ln(E_0/E_c))/\ln(\alpha + \beta)$ and the total energy lost in the shower is $E_{LT} = E_0(1 - (\alpha/(\alpha + \beta))^{N_c}$. From these considerations it can be shown that a break in the spectrum of about 0.3 above an energy of E_c can be produced if $\ln(\alpha)/\ln(\alpha + \beta) \approx 0.85$.

If we further assume that the total cross section for hadron production is larger for energies $> E_c$ then each leg of the cascade in this energy region will be shorter by an amount ϵ. Since the number of such legs is just N_c, the total amount the shower maximum will be raised is $\approx N_c \cdot \epsilon$, mimicking a shower produced by a heavier nucleus.

Combining the above effects we may produce a spectrum shown in Fig.(1.) and an elongation curve shown in Fig.(2.).

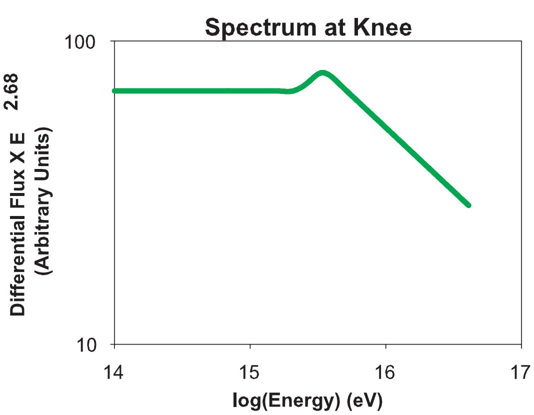

Fig. 1. Spectrum produced by energy loss in all collisions with energy above E_c

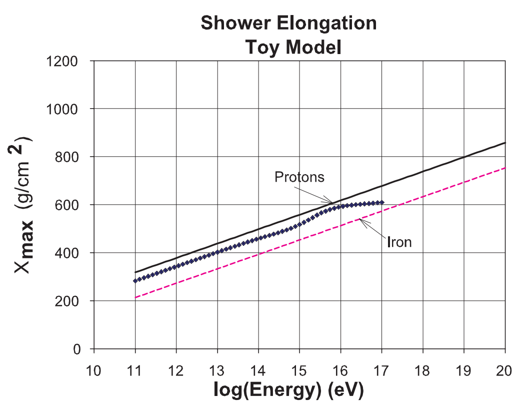

Fig. 2. Elongation produced in Toy Model

3. Problems with the model

Recent data from HiRes [1] indicates that the cosmic ray beam begins to trend back towards protons as its primary component at energies $> 10^{17}$ eV. In the current model, turning off the anomalous interactions above a super-critical energy, E_{sc} would cause the elongation curve to return to a track paralleling the one for protons but it would remain closer to that for iron and not return to the proton track as the data suggests it should. Further, if it turns out that the GZK cutoff is observed at the expected energy, a serious loss of energy is not tenable.

However, the present results are based on a highly simplified model of air showers in which the only observable component that builds up to a maximum and then decays is the hadronic component. In fact, by the time the shower has reached maximum a large fraction of the observable energy resides in the electromagnetic component. From this we may deduce that if there is a finite band of energy in which these enhanced or altered cross sections are in effect, for energies well above this band these effects may become less important in governing the development of the shower. Further, the Toy Model takes no account of leading particle effects in collisions. Such considerations remain for future work.

4. Problems with other models

There are, of course, other interpretations of the phenomenon of the knee. The notion that the spectral break and the trend toward heavier nuclei is the result of leakage from the Galaxy or cutoff of the acceleration mechanism at some maximum rigidity has been exhaustively investigated by Hörandel [7]. A problem with this approach is its extreme sensitivity to the assumed slope of the spectrum for each element, especially for iron. We have found that if one extrapolates iron from the HEAO[3] and JACEE [2] data with a spectral index of 2.73 the spectrum beyond the knee steepens by 0.6 rather than the observed value of 0.3. However, if a value of ~ 2.55 is assumed (see Grunsfeld *et al.* [5]) a good fit can be obtained up to about 10^{17} eV. Of course beyond this energy the spectrum cuts off exponentially rather than following the data. Hörandel [7] found that he could not extend this limit much further even by including elements up to uranium. He further suggested that some sort of "new physics" might be required to explain the knee.

5. Conclusion

There are several interpretations of the knee in the cosmic ray spectrum. All of them, including the present one suffer from defects. We therefore conclude that the knee is still a mystery.

References

[1] Abu-Zayyad, T. 2000, Phys. Rev. Lett. 84, 4276

[2] Asakimori, K. *et al.* 1998, ApJ 502, 278

[3] Engelmann,J. J. 1990, Astron. & Astro. 233, 96

[4] Fowler, J. W. *et al.* 2001 Astroparticle Physics 15, 49

[5] Grunsfeld, J. M. *et al.* 1988, ApJ 327, L31

[6] Heitler, W. 1944, *Quantum Theory of Radiation* (Oxford University Press) 2nd Edition

[7] Hörandel, J. R. 2003, Astroparticle Physics 19, 193

[8] Kazanas, D., Jones, F. C., Streitmatter, R. & Nicolaidis, A. 2001, 27th ICRC Hamburg, 1788

[9] Kazanas, D. & Nicolaidis, A. 2001, 27th ICRC Hamburg, 1760