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Cosmic Rays in the Energy Range 10^{14}–10^{17} eV

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Abstract

It is possible to explain the gross features of extensive air showers using very different alternative assumptions about the character of particle interactions, provided that different assumptions are made about the primary particle flux and composition. From this fact it is first shown that a very consistent set of fairly direct measurements on primary flux now exists (subject to the acceptance of a systematic bias in one set of data), together with constraints on the composition. (Protons and other nuclei however turn out not to have the same rigidity spectrum.) The gross features of showers mostly fit a scaling model with rising cross sections, but there are contrary indications (particularly from γ-ray flux, particle spread and core structure at the higher energies) that a change in the nature of interactions occurs above 10^{15} eV, and this puzzle has not been solved.

1. Introduction

Cosmic rays in the region around 10^{15} eV deserve special study for several reasons: diverse techniques of investigation applicable in different energy ranges almost overlap here, and it may be possible to check whether air showers really tell us an accurate story; the cosmic ray spectrum itself has an anomaly here, which should convey information about the origin of cosmic rays; emulsion and shower-core experiments have suggested that hadron interactions may show novel features here. This field is of interest to several Australian research groups.

Where the main interest of an investigation lies in particle physics rather than primary cosmic rays, information on the primary particles is still needed, for if features of the nuclear cascades are found to change with energy it is necessary to distinguish somehow between effects due to changes in the nature of the primary particles and changes in nuclear processes. It seems useful therefore to proceed as follows. After drawing on several sources to update the information on cosmic ray fluxes and species in the 10^{15} eV range, we will start with methods which require the least complicated analysis, and then see how well the new information accords with deductions drawn from air shower experiments by making use of some model of particle interactions. We will finally note some problems which arise in the comparison of models and data.

2. Cosmic Ray Energy Spectrum

The sources of information considered here are: (i) direct measurements (calorimeters, Cerenkov counters, etc.) up to about 1 TeV at balloon altitudes; (ii) the 'Proton' satellite calorimeters to about 10^{15} eV; (iii) atmospheric calorimetry at

10^{15}–10^{17} eV (shower size versus depth, and Cerenkov light calorimetry); (iv) high-altitude measurements of nucleon fluxes in emulsion chambers; and (v) high-energy muon fluxes (which require a particle production model for conversion to primary spectrum).

(*a*) *Direct Observations at Top of Atmosphere*

The fluxes of protons, α particles and various classes of nuclei measured in balloon experiments, and the fluxes of protons and all particles from the Proton satellites of Grigorov *et al.* (1971) are shown in Fig. 1. Here $I(E)$ denotes the flux of particles of a specific kind having energy greater than E, and the quantity $E^{1\cdot 5}I$ is plotted to avoid having steeply sloping plots with very many decades on the intensity axis.

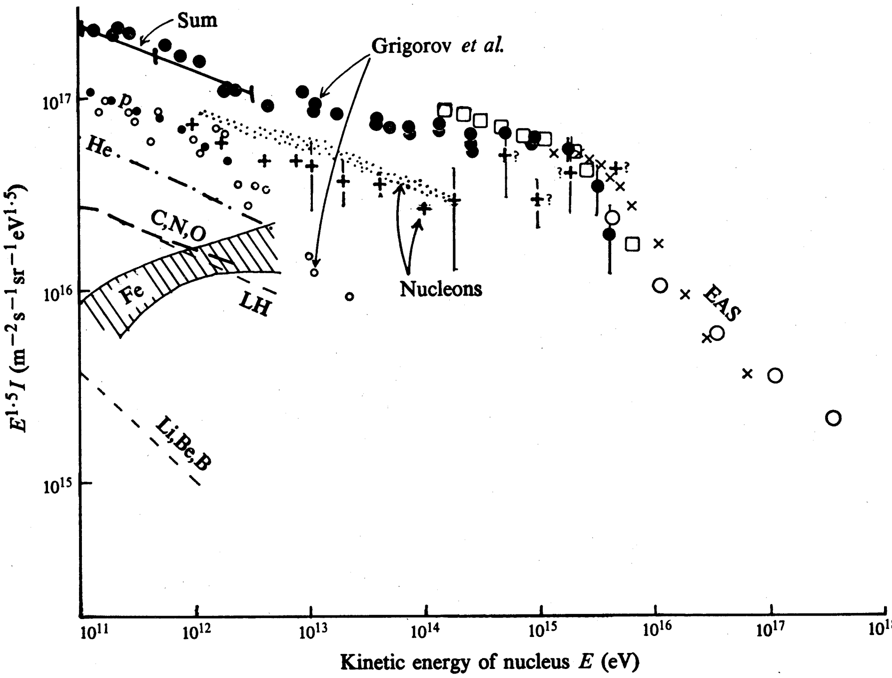

Fig. 1. Primary cosmic ray energy spectrum, where I is the integral flux. The results shown are those of Grigorov *et al.* (1971) for the 'all particle' flux (large solid circles) and the proton flux (small open circles) from the Proton satellite; the calorimetric measurements of the proton flux from balloons (small solid circles); the incoming 'nucleon' spectrum (pluses). Other values are as follows: large open circles, derived from the N versus t curves in Fig. 2; squares, derived from the size of vertical showers at Chacaltaya; crosses, the results of Efimov and Sokurov (1979) (see Section 2*c*). Other features are explained in the text.

The fluxes of the various nuclei observed by balloons may be added to give the total 'all particle' flux shown as the 'sum', which agrees well with that measured by the Proton satellites (large solid circles) in the region below 1 TeV where they can be compared. The latter measurements, from Grigorov's group, are still the only direct calorimetric measurements which extend to 10^{15} eV. (Although the proton component reported by the 'Proton' experiments is generally believed to fall off too steeply above 10^{12} eV, this is almost certainly a problem of particle identification and, according to R. W. Ellsworth and G. B. Yodh (personal communication), is related to the back-splash of a few tracks from the calorimeter, having no repercussions on the all particle flux.) The shape of the iron spectrum in Fig. 1 is still uncertain as indicated (and at low energies is much affected by solar modulation).

(*b*) *Deductions from Particles produced High in Atmosphere*

Emulsion chambers exposed in high-flying jet aircraft (Iwai *et al.* 1979) have yielded a spectrum of nucleons, which has been extrapolated to the top of the atmosphere to give the incoming 'nucleon' spectrum, where all nucleons are counted individually whether they enter singly or bound in nuclei. These are marked by a 'plus' in Fig. 1; those with a 'question mark' have values that are probably too high, though by less than a factor of 2.

Well established techniques can be used to measure the spectrum of high-energy muons; these largely come from the decay of mesons produced in the first interactions of the primary particles, where to a good approximation the various nucleons in the primary nuclei interact independently, and so again it is the influx of all nucleons which determines the result. If one takes the data on pion and kaon production from accelerators and assumes that 'radial scaling' (as described in Section 4) is still valid when extrapolating these production cross sections to 10^{14} eV, the nucleon spectrum needed to reproduce the observed muons can be calculated. It is found that the muon flux at E TeV essentially determines the nucleon flux in a limited range around $12E$ TeV. The stippled band in Fig. 1 shows the resulting nucleon spectrum. (The MUTRON horizontal muon spectrometer indicates that the nucleon spectrum may fall a little more steeply beyond 10^{14} eV, which may perhaps reflect the first spectrum 'knee' which will appear later in Fig. 3. The horizontal spectra were not used in the present paper; see Allkofer (1979) for comments on the different spectra available.) The result is very close to the spectrum obtained from emulsion chambers, and below 1 TeV accords with the nucleon spectrum derived from spectra of all individual nuclei.

(*c*) *Energy deposited in Atmosphere by Air Showers*

The curve for shower size N versus atmospheric depth t should give the best estimate of the energy of the shower, as over 90% of the incident energy is dissipated in ionization, which is proportional to $\int N\,dt$, and errors in the correction made for the remainder cannot be significant. Because they extended so high in the atmosphere, the Chacaltaya experiments are most important in deriving this integral, but even in the earlier series of measurements there were problems in relating shower sizes measured by the Chacaltaya groups with those of other experiments. Thus, if the curves of $N(t)$ corresponding to primaries arriving at the specified rates I (e.g. 10^{-6}, $10^{-7}, \ldots, 10^{-11}\ \mathrm{m^{-2}\,s^{-1}\,sr^{-1}}$) from different experiments are plotted on the same graph, it appears that there is a systematic displacement between the results from Chacaltaya and from apparatus lower in the atmosphere. Except for the smallest showers, the N values from the Chacaltaya inclined showers systematically lie above those obtained at Tien Shan (Danilova *et al.* 1977), Volcano Ranch (Linsley 1973) and sea level (data from Moscow, MIT, Yakutsk and Kiel; see Hillas 1975). To show this, the (old) Chacaltaya data of LaPointe *et al.* (1968) have been plotted in Fig. 2 (large circles) after having reduced the N by a factor of 1·5. The data then fit the low-altitude results fairly well. The values of N from the new Chacaltaya experiment are higher still, the discrepancy arising from the lateral structure functions used in the analysis. The measurement of N for showers, and particularly young showers, is not easy and as yet it cannot be certain who is right; for the present though, the great majority will be assumed to be right and the N values plotted in Fig. 2 will be used.

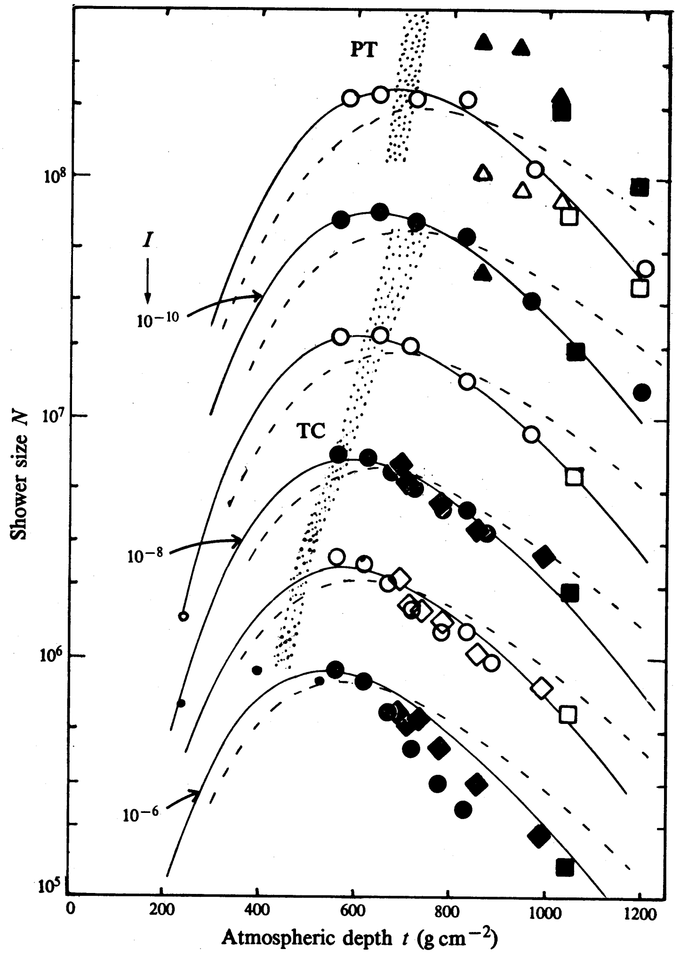

Fig. 2. Shower sizes N at selected integral rates I ($m^{-2} s^{-1} sr^{-1}$) shown for the data at Chacaltaya (circles), Tien Shan (diamonds), Volcano Ranch (triangles), sea level stations (squares) and aircraft (small circles). The stippled bands PT and TC show the position of maximum N estimated from Cerenkov pulse observations by Protheroe and Turver (1977) and Thornton and Clay (1979) respectively. The predictions of scaling models are shown both with (full curves) and without (dashed curves) inclusion of rising cross sections at higher energies (see Section 4).

To integrate $\int N\,dt$, one has to complete the curve in the unobserved range of t. The curves drawn in Fig. 2 were used for this continuation, and although they were derived from a particular model—a scaling model with rising cross sections (Hillas

1979)—other models which fit the data at $t > 550\ \mathrm{g\,cm^{-2}}$ give very similar continuations at $t < 550\ \mathrm{g\,cm^{-2}}$, and would give very similar integrals and hence energies. There is a check on the depth at which N is a maximum, in the case of the largest showers, from the pattern of emission of Cerenkov light in the atmosphere. The preliminary results of Protheroe and Turver (1977) shown in Fig. 2 agree well, though Thornton and Clay (1979) deduced that the maximum N occurred at smaller t than shown by the curves from their Cerenkov pulse measurements. Very high altitude measurements on aircraft by Antonov *et al.* (1977) (see also Stamenov and Ushev 1977) also point to a greater N high in the atmosphere for the smallest showers, and cannot be fitted on these curves. The reason for this may be that there is another component present, developing very rapidly in the upper atmosphere, or the shower sizes are not being correctly derived, or the energy estimates for the smallest showers will have to be increased. For the present, these aircraft measurements will be ignored.

The area under the lowest curve in Fig. 2 is not well determined, but the next one gives $E = 3 \cdot 8 \times 10^{15}$ eV after allowing for neutrinos etc., and E can similarly be derived for the other curves, giving the results shown (large open circles) in Fig. 1. In order to take the energy spectrum below $3 \cdot 8 \times 10^{15}$ eV, E has been derived (with greater uncertainty) simply from the size N of vertical showers at Chacaltaya (still reduced by a factor $1 \cdot 5$ as before) using the scaling model referred to above. At the lowest energies the conversion depends increasingly on the mass of the primary particle: a typical mass 12 has been assumed, in line with the low-energy composition, to give the spectrum indicated by the squares in Fig. 1, down to about $1 \cdot 5 \times 10^{14}$ eV.

Finally, the observation of Cerenkov light from the sky can be used to integrate the track length of electrons in the atmosphere and obtain the shower energy. Although great weight should perhaps not be placed as yet on this experiment, it is instructive to plot the results of Efimov and Sokurov (1979) in the range 10^{15}–3×10^{16} eV, as shown in Fig. 1 (crosses).

It is remarkable how well the different calorimetric spectra agree around 10^{15} eV. Although the direct measurements of Grigorov *et al.* (1971) with their Proton satellites seemed low when first produced in 1965, they now fit air shower data ('reduced' as noted above) very well. Of course, it is possible that both are in error. Air shower energies could be a little higher (the Antonov *et al.* (1977) results having been ignored and the Chacaltaya N values forced down to meet the others), and it could be that the satellite calorimeter underestimated the highest energies somewhat if a greater fraction of the large bursts leaked from the bottom of the calorimeter. In this paper both measurements will be assumed correct.

3. Primary Composition

The primary composition is strongly constrained by the spectrum of all particles (nuclei) and the 'nucleon' spectrum. This point will be considered before the more model-dependent deductions from air shower data are referred to.

(*a*) *Constraints imposed by Nucleon Flux near* 10^{14} eV

In short, the primary proton flux cannot lie very far below the 'nucleon' flux. For a pure proton beam, the flux of nuclei of energy E would be the same as the flux of nucleons of energy E, which it is not. If all nucleons arrived bound in iron nuclei, having an integral energy spectrum (for nuclei) $HE^{-\gamma}$, the nuclei would have an energy

56 times higher than the nucleons, but would be reduced in number by a factor of 56, resulting in a 'nuclei' flux $56^{\gamma-1}$ times higher—say 8–13 times higher—than the nucleon flux. In fact, the actual ratio of fluxes near 10^{14} eV seems to be close to 2. One can examine the fluxes arising from a crude mixture of protons with integral flux $PE^{-\gamma}$, heavy (iron) nuclei with flux $HE^{-\gamma}$ and intermediate nuclei with flux $ME^{-\gamma}$ (and effective mass in this context of about 7 or 8). If $H = 0{\cdot}5\,M$, as suggested at lower energies, one requires the proton flux to be about 0·65 of the 'nucleon' flux to produce a ratio of 2 for nuclei to nucleons. Taking extreme limits of 1·7–2·8 for the latter ratio would correspond to 0·75–0·37 for the ratio of primary protons to 'nucleons'. A more iron-rich nuclear mixture than this would raise the protons closer to the 'nucleons'. The hexagonal point P in Fig. 3 marks this deduced value of the proton flux.

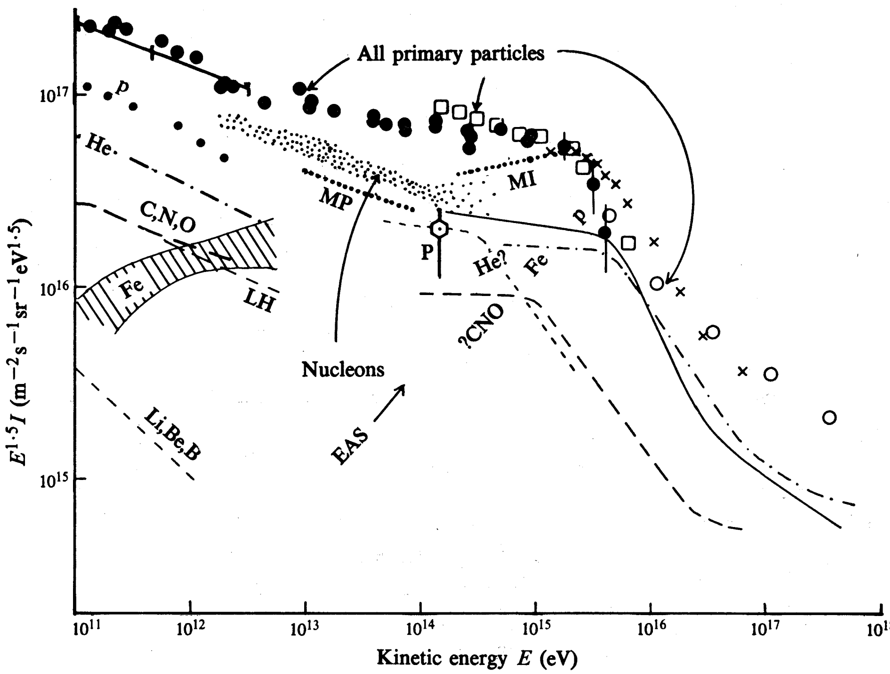

Fig. 3. Primary energy spectrum with the data of Fig. 1, but including the estimates of spectra of various nuclear components above 10^{13} eV (see text).

(b) Spectra of Various Nuclear Components needed for Consistency with a Scaling Model of Air Showers

A scaling model taking particle interaction processes from accelerator data (Hillas 1979) and referred to again below has been used to find what primary fluxes are needed to reproduce the shower size N_e spectrum and N_μ spectrum at sea level and Tien Shan, and to accord with the all particle spectrum up to 10^{15} eV of Grigorov *et al.* (1971). As only the crudest information on composition could be expected, it was assumed in the first place that all nuclei other than hydrogen had the same spectral form of energy per nucleon, but the proton spectrum was adjusted independently of the others. The relative numbers of the other nuclei were suggested by low-energy data, although the relative number of iron nuclei was not so constrained. The results are shown in Fig. 3.

The sensitivity to composition largely arose from the fact that with the range of parameters examined protons turn out to dominate the N_e spectrum before the 'knee' (though less so at Tien Shan), whilst other nuclei completely dominate the N_μ size spectra (though unfortunately these spectra at sea level rely on a slightly indirect determination by the Moscow University group). Although the flux of protons relative to other nuclei was not fed into the calculation, the results shown in Fig. 3 are entirely consistent with a continuation of the low-energy fluxes.

A surprising feature is that the knee in the proton spectrum occurs at about the same energy as in the iron spectrum, rather than 26 times lower as would be expected if the spectral shape were determined by magnetic trapping effects. In fact, the shape of the all particle spectrum alone (from air-shower calorimetry) rules against the picture in which the proton flux falls off first at energy E_k and the other nuclei at successively higher energies ZE_k. The fall is rather sharp, whereas a more gradual drop would have resulted from the successive removal of other nuclei after starting with the most abundant one. The implications for the origin of cosmic rays will not be discussed here.

(*c*) *Evidence from Core Structure of Showers*

McCusker (1975) has summarized the striking results of the Sydney 64-scintillator experiment and the main features of their interpretation. For shower sizes just above that corresponding to the knee in the spectrum, very steep-cored showers unexpectedly disappeared. This feature is needed also to explain the sudden steepening in the density spectrum of locally detected showers (McCaughan 1975). The explanation put forward is that at this point protons disappear from the primary beam, leaving it dominated by heavier nuclei. (As α particles can generate quite steep cores, it would certainly help if α particles had already disappeared before this point.) For energies below 10^{15} eV, McCusker envisages a proportion of protons very similar to that indicated in Fig. 3, although he would presumably require the proton flux to fall off more sharply below the flux of heavy nuclei than is shown, in order to explain the rapid loss of single-cored showers. However, at energies above the knee, there are other complications, as the intrinsic spread of secondary products from interactions seems unexpectedly to increase.

(*d*) *Other Evidence*

The composition proposed in Fig. 3 gave a reasonable account of the fluctuations in the N_μ/N_e ratio observed at Moscow for different shower sizes: with a scaling model a mixture of protons and iron nuclei is more effective than protons alone in producing fluctuations. Using a different particle production model (CKP) however, Nikolsky *et al.* (1979) concluded that protons made up about 60% of the primaries at 10^{15} eV. (It might be hard to accommodate quite so many protons without a greater flux of 'nucleons', but these authors would not rule out 40%, as in Sections 3*b* and 3*c* above.)

The Maryland group (Goodman *et al.* 1979) have come to a different conclusion about the iron flux from their studies of delayed hadrons accompanying showers. They propose the spectra marked MP and MI for protons and iron nuclei in Fig. 3.

It seems hard to get so many iron nuclei within the all particle spectrum. The analysis does depend on following hadrons right through the atmosphere in Monte Carlo simulations, and also on the NKG particle densities near the shower axis which may well be inaccurate according to recent cascade simulations.

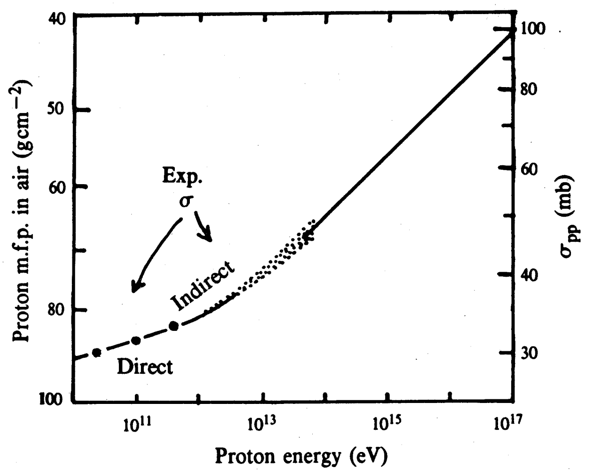

Fig. 4. Experimental pp cross sections obtained at CERN (converted to the inelastic part) and the $(\log E)^2$ extrapolation. The left-hand ordinate shows the conversion to the inelastic proton mean free path in air.

4. Successes of Scaling Models of Particle Interactions

In the reaction $a+b \rightarrow c+$anything, the differential cross section for production of c having energy E and momentum p is supposed to take the form

$$E\,\mathrm{d}^3\sigma/\mathrm{d}p^3 = \sigma_{ab}\, f_{abc}(x, p_t) \qquad (1)$$

at energies which are not too low. Here $x = E/E_0$, where E_0 is the maximum available energy, taken to be half the c.m. energy if working in the c.m. system, to which equation (1) strictly applies. (At high energies, the same relationship holds quite well in the lab. frame, E_0 now being the total collision energy.) Thus the rate of production of a particular kind of particle depends on the fraction x of the total energy which it takes, whatever the primary energy, and the actual distribution functions f may be determined at accelerator energies. (The Feynman scaling variable $x = p_L/p_{max}$ is less successful.) An important complication is that total interaction cross sections appear to rise considerably as one approaches air shower energies. From scattering experiments at CERN (Amaldi *et al.* 1977), the pp total cross section is deduced to rise considerably by 10^{14} eV (see Fig. 4), and a simple extrapolation suggests that σ_{pp} will have tripled in going from 10^{11} to 10^{17} eV, while the inelastic $\sigma_{p,air}$ would have doubled. It is assumed that when the inelastic cross section σ_{ab} rises, all partial cross sections rise proportionately as shown by equation (1), though this effect cannot be tested as yet with accelerators. If the rise in cross section is not allowed for, scaling models of air shower development reach shower maximum too deep in the atmosphere, at the highest energies, as indicated by the dashed curves in Fig. 2. This was one reason for early doubts about scaling, but with the rising cross section taken into account (and the mixed composition), a much better description of longitudinal development is obtained (see the full curves in Fig. 2).

The data for N_μ versus N_e at sea level and Tien Shan are properly described, and the reasonableness of the required proportion of protons may be taken to indicate that the predicted proportion of muons is satisfactory. However, showers probably have fewer high-energy hadrons than predicted.

The familiar $E^{1/4}$ multiplicity law for pion generation with fireballs, as opposed to scaling (in which the number of particles having more than 1 or 2% of E_0 is constant and the total multiplicity rises quasi-logarithmically), gave very similar longitudinal development curves with a constant inelastic cross section, but this now seems less realistic. Also, using a scaling model, Ellsworth *et al.* (1979) have simulated emulsion chamber jet events, and shown that selection biases generate many apparently non-scaling features reported, such as high-mass fireballs, higher multiplicities and rapidity densities, and p_t–fireball-mass correlations. However, there are problems with this model.

5. Evidence of Serious Departures from Scaling near 10^{15} eV

There seem to be two problems concerning numbers of particles, as distinct from angular distributions. The flux of 'γ rays' (though electrons are always included also) in the 1–100 TeV range in the atmosphere is about a factor of 3 below that predicted by scaling models. Akashi *et al.* (1979) using the calculations of Kasahara interpret this and other fluxes measured in emulsion chambers as evidence for a sharing of energy amongst more secondary particles, close to the old $E^{1/4}$ law. It is surprising in this case that the muons seemed to come out right with scaling, and also that there is such a discrepancy near 1 TeV, close to the range verified by accelerators. The γ rays must reflect neutral pion production at appreciably higher energies, and possibly pion collisions are largely to blame for the discrepancy. Still, this is a serious matter when it comes to interpreting mesons in air showers. Also, the number of TeV hadrons in air showers of 10^{15}–10^{16} eV seems somewhat smaller than that predicted by most models (the observations being made at mountain altitudes), though there are still considerable discrepancies among the different experiments.

The strange 'Centauro' events have been known for several years now, but we still know little more about them than at first. They are seemingly not uncommon at around 10^{15} eV (but not so common to account for the paucity of neutral pions just referred to). Another directly observed feature hard to understand on the basis of scaling is the number of high-multiplicity events (n approaching 100) seen in emulsions.

But one of the most striking features observed in air showers relates to the lateral spread of the high-energy particles. The Sydney experiment on core structure showed a rapid rise in transverse momentum had occurred at 10^{16} eV primary energy, as the spread of the high-energy constituents of the core did not contract with increasing energy. In addition, McCaughan (1975) required shower cores to flatten suddenly at about this energy to explain the sudden steepening of the local density spectrum. Further progress in understanding core structure has been slow, and several reasons have contributed to this. It seems that one is dealing with simultaneous changes in interaction characteristics (at the very least concerning p_t) and in the primary composition and spectral shape. (Incidentally, it is not easy to make a plausible model in which these are causally related!) And it is clear that the actual appearance of distinct subcores (rather than a smooth broad particle distribution) is very greatly affected by the material of the detectors used and the roof. A. L. Hodson reports (personal communication) that striking subcores are obvious visually in the Norikura discharge chamber photographs (where there are thick roof beams), but are rare in a similar array at Leeds until a beam is added, leading to the appearance of dense cores. Further work remains to be done on the correction for material so close to the core making cascades look younger: the use of averaged ratios of signals seen in different detectors can be misleading here, so the quantitative derivation of individual p_t values is still uncertain.

Also, there have been persistent reports that the proportion of neutral TeV hadrons seen in cloud chambers is much higher than expected from a scaling model. Although the production cross section of antinucleons seen at CERN was at first thought to promise copious production at air shower energies, the extrapolation of present data from simple scaling (Hillas 1979) suggests that under 3% of the collision energy would go into nucleon pair production.

6. Conclusions

In our ignorance, we can do quite well with scaling models to analyse showers at 10^{17} eV and above, whereas it is clear that problems have arisen at lower energies. It would be helpful if the very considerable detector-dependent and overlay-dependent effects in the vital experiments on core structure could be elucidated sufficiently to permit more quantitative conclusions to be drawn.

Because of the importance of calorimetry in the atmosphere in keeping models on the right track, the difficulties in coming to mutually agreed size measurements on high mountains is disturbing. Cerenkov calorimetry from the Utah experiment will therefore be very significant, and it should also help materially in constraining the composition around 10^{16} eV from the fluctuations in height of shower development. There is at present some uncertainty about the composition here, as the Sydney core experiment indicated a very large depletion in proton showers had occurred at this energy (McCusker 1975). However, no large anomaly in the proportion of muons in showers or in the fluctuations in that proportion was seen in the Moscow experiments spanning that size range, nor in other experiments, and this has led many workers to conclude that proton showers are still present to an appreciable extent. We probably need to know more about the other underlying causes of the change in core structure, mentioned above, to resolve this problem.

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References

Akashi, M., *et al.* (1979). Proc. 16th Int. Conf. on Cosmic Rays, Kyoto, Vol. 6, p. 344 (Univ. Tokyo Press).

Allkofer, O. C. (1979). Proc. 16th Int. Conf. on Cosmic Rays, Kyoto, Vol. 14, p. 385 (Univ. Tokyo Press).

Amaldi, U., *et al.* (1977). *Phys. Lett.* B **66**, 390.

Antonov, R. A., Astafiev, V. A., Ivanenko, I. P., and Kopylova, T. M. (1977). Proc. 15th Int. Conf. on Cosmic Rays, Plovdiv, Vol. 8, p. 137 (Bulgarian Academy of Sciences: Sofia).

Danilova, T. V., *et al.* (1977). Proc. 15th Int. Conf. on Cosmic Rays, Plovdiv, Vol. 8, p. 129 (Bulgarian Academy of Sciences: Sofia).

Efimov, N. N., and Sokurov, V. F. (1979). Proc. 16th Int. Conf. on Cosmic Rays, Kyoto, Vol. 8, p. 152 (Univ. Tokyo Press).

Ellsworth, R. W., Yodh, G. B., and Gaisser, T. K. (1979). Proc. 16th Int. Conf. on Cosmic Rays, Kyoto, Vol. 6, p. 312 (abstract) (Univ. Tokyo Press); Proc. American Inst. Phys. Conf. on Cosmic Rays and Particle Physics, No. 49 (Bartol Conf. 1978) (Ed. T. K. Gaisser), p. 111.

Goodman, J. A., *et al.* (1979). Proc. 16th Int. Conf. on Cosmic Rays, Kyoto, Vol. 8, p. 32 (Univ. Tokyo Press).

Grigorov, N. L., *et al.* (1971). Proc. 12th Int. Conf. on Cosmic Rays, Hobart, Vol. 5, p. 1746 (Univ. Hobart Press).

Hillas, A. M. (1975). *Phys. Rep.* C **20**, 59.

Hillas, A. M. (1979). Proc. 16th Int. Conf. on Cosmic Rays, Kyoto, Vol. 6, p. 13; Vol. 9, p. 13 (Univ. Tokyo Press).

Iwai, J., Ogata, T., Ohta, I., Takahashi, Y., and Yanagita, T. (1979). Proc. 16th Int. Conf. on Cosmic Rays, Kyoto, Vol. 8, p. 1 (Univ. Tokyo Press).

LaPointe, M., *et al.* (1968). *Can. J. Phys.* **46**, S68.

Linsley, J. (1973). Proc. 13th Int. Conf. on Cosmic Rays, Denver, Vol. 5, p. 3207 (Univ. Denver Press).

McCaughan, J. B. T. (1975). Ph.D. Thesis, University of Sydney.

McCusker, C. B. A. (1975). *Phys. Rep.* C **20**, 229.

Nikolsky, S. I., Kabanova, N. V., Stamenov, J. N., and Janminchev, V. D. (1979). Proc. 16th Int. Conf. on Cosmic Rays, Kyoto, Vol. 8, p. 335 (Univ. Tokyo Press).

Protheroe, R. J., and Turver, K. E. (1977). Proc. 15th Int. Conf. on Cosmic Rays, Plovdiv, Vol. 8, p. 275 (Bulgarian Academy of Sciences: Sofia).

Stamenov, J. N., and Ushev, S. Z. (1977). Proc. 15th Int. Conf. on Cosmic Rays, Plovdiv, Vol. 8, p. 133 (Bulgarian Academy of Sciences: Sofia).

Thornton, G., and Clay, R. (1979). *Phys. Rev. Lett.* **43**, 1622.

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