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Comment on the Cosmic Ray Energy Spectrum in the Light of Results from Atmospheric Cerenkov Studies

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Abstract

New information has recently become available on the development of cosmic ray showers in the atmosphere. This information is used to show that the energy spectrum of cosmic rays must exhibit more pronounced structure than previously thought at energies of about 10^{16} eV. Possible interpretations of this structure are discussed.

1. Introduction

In recent years new evidence has become available on the development of extensive air showers from experiments employing the detection of Cerenkov light emitted by the showers in their passage through the atmosphere. The first published evidence was originally controversial (Thornton and Clay 1979*b*, 1981; Orford and Turver 1980) but appears now to have been experimentally confirmed by several groups (Inoue *et al.* 1981; Kuhlmann and Clay 1981; Andam *et al.* 1982). We wish to examine some of these new data and combine them to obtain new insight into the energy spectrum of the primary cosmic ray particles.

A knowledge of the cosmic ray energy spectrum is basic to our efforts to understand the properties of the cosmic ray flux. At energies up to about 10^{14} eV the spectrum has been measured directly using satellites and its form is relatively uncontroversial. At energies above 10^{17} eV, the spectrum is studied through giant air showers together with the use of reasonably model-independent cascade calculations. A problem arises at the intermediate energies 10^{14}–10^{17} eV. Shower models are uncertain in this region, with recent measurements by atmospheric Cerenkov techniques indicating that shower development changes rather rapidly with energy at least in the vicinity of 10^{16} eV, an unexpected result (Thornton and Clay 1979*a*). The difficulty is that, whilst the cosmic ray shower-size spectrum at ground level is itself relatively uncontroversial, the conversion of that spectrum to an energy spectrum is not at all straightforward.

The Cerenkov technique samples the whole of the shower development and can be used not only to measure the depth of shower maximum but also to give a rather direct measurement of shower primary energy (Andam *et al.* 1982). Cerenkov data may be combined with well-known particle size spectrum data to derive an energy spectrum. We present two such energy spectra below, derived in somewhat different

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ways. It will become clear that current ideas on the energy spectrum between 10^{16} and 10^{17} eV require revision.

2. Cerenkov Data on Shower Development

The body of experimental data which we use as a basis for our discussion is contained in two papers (Thornton and Clay 1981; Andam *et al.* 1982). These papers relate, in one case, the depth of shower maximum to sea-level shower size and, in the second case, the depth of shower maximum to shower primary energy. The first set of data is from Cerenkov experiments conducted in conjunction with a conventional air shower particle array and the second set of data is from Cerenkov experiments alone. Both sets of data exhibit a similar feature, a rather rapid increase in depth of shower maximum with shower size (or energy) over a limited size (or energy) range. We wish to compare the two sets of data in this size (energy) range on the assumption that both experiments observe similar showers developing at similar depths of maximum, i.e. that we can use the depth of maximum to identify a sea-level shower size with a total shower energy.

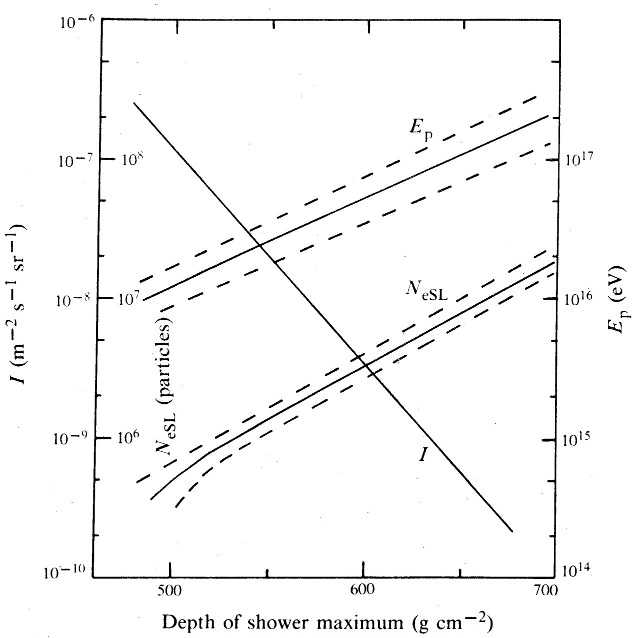

Fig. 1. Relationships between depth of shower maximum and sea-level shower size N_{eSL}, primary energy E_p and integral intensity I. Data on size and energy are derived from Thornton and Clay (1979*b*) and Andam (1982). Integral intensity data are derived from the size relationship and the integral size spectrum. Dashed curves indicate the spread in the data used.

We have fitted a function to each set of the experimental results and these are shown in Fig. 1 where shower primary energy E_p and sea-level size N_{eSL} are related to depth of shower maximum. Since the shower size spectrum (size against integral intensity) is well known (Hillas 1975; Clay and Gerhardy 1982), we can also relate an intensity I to a depth of shower maximum through the shower size. This relationship is also shown in Fig. 1.

Fig. 1 can be checked for consistency with conventional wisdom through the relationship it gives between sea-level shower size and primary energy. We expect a relationship which has the shower size increasing somewhat faster than proportionally with primary energy (due to an increase in depth of maximum with energy/size and hence reduced attenuation after maximum). The resultant expression is

$$N_{\mathrm{eSL}} = 5{\cdot}3\times 10^5(E_\mathrm{p}/10^{16})^{1\cdot 2}.$$

Allan (1971) used a simple conventional air shower model to derive a corresponding relationship and found

$$N_{\mathrm{eSL}} = 10^6(E_\mathrm{p}/10^{16})^{1\cdot 15},$$

which agrees well with our result from experimental data. We conclude that the results from the Cerenkov work are reasonable.

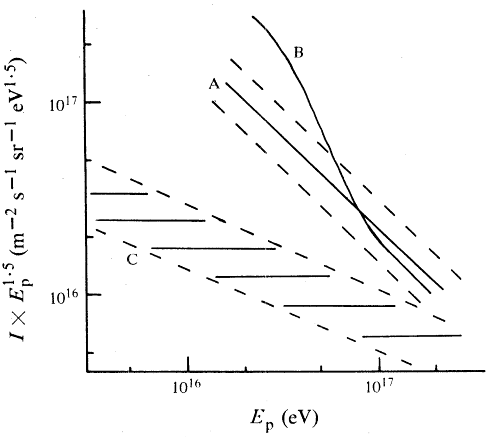

Fig. 2. Cosmic ray energy spectra derived (A) directly from data in Fig. 1, (B) from the size/depth relationship in Fig. 1, the shower size spectrum and the assumption that shower size at maximum is proportional to primary energy, (C) by Hillas (1980).

3. Derivation of Energy Spectrum

Since Fig. 1 relates both integral shower intensity and primary energy to depth of maximum, we can directly derive an energy spectrum, namely

$$I = 2\times 10^{-7}(E_\mathrm{p}/10^{16})^{-2\cdot 5} \qquad (10^{16} \leqslant E_\mathrm{p} \leqslant 2\times 10^{17}\ \mathrm{eV}).$$

The resulting spectrum (A) is shown in Fig. 2 together with a spectrum (C) derived by Hillas (1980) from other (non-Cerenkov) data. These spectra differ appreciably and we wish to check our Cerenkov-derived spectrum. We can return to a single Cerenkov experiment and use the measured depth of shower maximum against sea-level size and the sea-level size spectrum to estimate an energy spectrum. One can use rather general arguments involving the sea-level shower-size spectrum and the Cerenkov relationship between sea-level size and depth of shower maximum to derive a non-normalized energy spectrum (which can then be normalized to other data at $\sim 10^{17}$ eV).

The sea-level shower size of an air shower (number of shower particles at sea level) depends on the shower primary energy and the way in which the shower develops in the atmosphere. As a rough rule, however, the number of particles at shower maximum depends only on (and is proportional to) the shower primary energy. Also, attenuation well past maximum follows a known exponential form (with an *e*-folding depth known as the attenuation length which is almost energy independent). Thus, if one had two showers of similar primary energy (in our energy range) but differing depth of maximum, their sea-level size would differ simply by a factor equal to the shower attenuation in an atmospheric depth equal to the difference in depths of maxima. Development near maximum does not affect this result provided that, in terms of absorber depth (in $\mathrm{g\,cm^{-2}}$), average development progresses similarly in both cases. This assumption appears to be borne out by calculated development curves such as those by Hillas (1980). In the restricted shower-size range of interest, the available data (e.g. Clay and Gerhardy 1982) indicate constancy of the mean attenuation length. Cerenkov measurements tell us the average depths of maximum of showers of known sea-level sizes, so that development effects may be allowed for when considering the measured (and well-known) size spectrum.

A reasonable, but arbitrary, value for the size at shower maximum was chosen for a sea-level shower size of 10^7 particles; a shower maximum size was then derived for smaller showers, on the assumption that sea-level size equals shower maximum size multiplied by an attenuation factor due only to the different depths of maximum, assuming an attenuation length of $185\ \mathrm{g\,cm^{-2}}$ (see Clay and Gerhardy 1981). Thus a spectrum of shower maximum sizes was derived. Since shower primary energy is believed to be closely proportional to shower size at maximum, this spectrum may be converted to an energy spectrum by a scale re-labelling and an adjustment of the scales by a constant multiplier, chosen to give a conventional sea-level size at $\sim 2\times 10^{17}$ eV. This energy spectrum is also shown in Fig. 2 (spectrum B) and exhibits a departure from the conventional spectrum C similar to that shown by the previous, more directly derived, spectrum A. The derivation of spectrum B makes it clear that the discrepancy occurs because the conventional spectrum interpretation does not take into account the observed rapid change in depth of maximum with shower size.

4. Discussion of Energy Spectrum

A result following from the observation of a rapid change in depth of shower maximum with shower size or energy is that the knee in the primary energy spectrum must be sharper than thought previously. This conclusion is general and independent of any detailed calculation since the effect of including this change is to raise the derived shower energy for a fixed cosmic ray flux for sea-level sizes below 10^7 particles. Not only is the knee sharpened but also, as a consequence of the steepness of the measured shower spectrum, its intensity at a given energy is increased. A corollary of this is that a gap in available spectral data appears between $\sim 10^{14}$ and 10^{15} eV. We are left therefore with an appreciable 'bump' in the spectrum whose shape is indeterminate between 10^{14} and 10^{15} eV and which cuts off rapidly above $\sim 10^{16}$ eV.

The energy spectrum B shown in Fig. 2 is remarkable in the sense that the knee of the spectrum is now clearly accentuated and appears to stand out as a peak above a line which one might imagine joining the upper and lower portions of the spectrum. The direct independent evidence to check the primary energy spectrum in this range is limited. The measurement of the density spectrum of Cerenkov radiation may help in this respect since the Cerenkov shower size is expected to be a good measure of the total shower energy although, since the lateral distribution function changes rapidly with energy, the interpretation is not straightforward. An example of such a measurement is the work of Efimov and Sokurov (1979). These data do show an unusual result between 10^{15} and 10^{16} eV. As the data stand, they agree neither with the conventional primary energy spectrum nor with the spectrum presented here. However, if the energy assignation of Efimov and Sokurov was in error by a factor of $\sim$2–3, agreement with our proposed spectrum would be excellent. This error would not necessarily be surprising since the conversion factor relating measured Cerenkov density to primary energy is one of the most difficult problems in interpreting the experimental data. The spectrum presented here is in disagreement with data obtained by Grigorov *et al.* (1971), who used a satellite calorimeter. However, the energies involved are at the extreme of the range of the satellite instrumentation. The calibration of the satellite equipment may be suspect for this reason. Kempa *et al.* (1974) obtained a similar spectrum to ours from a study of air shower development using published data taken at a number of altitudes.

The origin of a possible excess in the energy spectrum has been discussed, for instance, by Karakula *et al.* (1974) who predicted such an excess by considering the contribution to the spectrum of protons accelerated by pulsars. This picture is not as satisfactory as it appears since it offers no explanation of the change in depth of shower maximum with shower size. A simple explanation of this phenomenon would be that the composition of the particles in the peak is dominated by heavy (presumably iron) nuclei (Thornton and Clay 1979*b*). A major attraction of the result of Karakula *et al.* is that these authors were able to predict the spectrum shape and flux rather well with few free parameters by using the pulsar acceleration model by Ostriker and Gunn (1969). However, if this model is employed for iron primaries (perhaps a natural composition for a pulsar source), the position of the peak should be moved upwards by a factor of $\sim$40 in energy and the fit of the simple model ceases to be satisfactory. Thus, one can argue for a pulsar-accelerated second component but, whilst the general shape of the spectrum of this component is reproduced well, the mechanism cannot be just the Ostriker and Gunn model since the energies are incorrectly predicted. One can derive the shape of the secondary component of the spectrum on the assumption that the 'primary' spectrum continues without structure between 10^{14} and 10^{17} eV. The shape of this new component is remarkably similar to the pulsar spectrum discussed by Barrowes (1971).

It may be possible to invoke an alternative interpretation of the change in depth of maximum against shower size. This would be that a new interaction process becomes important above $\sim 10^{15}$ eV. This might involve a resonance, with the effect of causing particle interactions in a limited energy range to occur with a short mean free path. Thus shower maximum would appear excessively early whilst the resonance affects the early shower cascade interactions which determine the number of particles at shower maximum. As primary energies increase (up to about a factor of 10 above the resonance energy), progressively less effect on shower maximum would be found as the secondaries of the resonance interaction *affect shower maximum* less. This scenario can also explain the general dependence of depth of maximum on shower size below $\sim 10^5$ particles, if one takes into account the effect of fluctuations in shower development. The greatest change in depth of maximum would be roughly the interaction mean free path of primary protons or $\sim 100\,\mathrm{g\,cm^{-2}}$. Thus, all the major features of the dependence of depth of maximum on shower size may be explicable. The shape of the primary energy spectrum may also be a result of such an interaction process near the source of cosmic rays. If one postulates a dense source of high-energy particles such as the supernova model discussed by Barrowes (1971) then one would expect any particles accelerated to $\sim 10^{15}$ eV to interact with the local environment (e.g. a supernova shell). Two effects would follow from a resonance interaction model. Firstly, there would be a depletion of particles immediately above 5×10^{15} eV since particles which would otherwise have been accelerated to these energies would have interacted. Secondly, the secondary particles from the interaction would produce an excess of particles (secondaries) at energies immediately below the resonance. In general terms this is the observed shape of the spectrum. Thus, the scenario of a new resonant interaction for protons at $\sim 10^{15}$ eV provides a possible explanation of the data on both depth of maximum and primary energy spectrum. We note that McCaughan (1981) also required new interaction properties at 10^{15} eV to explain his density spectrum results.

5. Conclusions

Using specific examples, we have shown that if one converts the cosmic ray shower-size spectrum into a primary energy spectrum using the recently measured atmospheric Cerenkov data, then the primary energy spectrum exhibits a prominent feature at $\sim 3\times 10^{15}$ eV. This feature is very suggestive of a second component being present in the cosmic ray beam, superimposed on a primary component. The secondary component bears a striking similarity to the component predicted by Karakula *et al.* (1974) from a consideration of pulsar acceleration contributions to the cosmic ray flux, but interpretation of the results in this way is not without complications.

Alternatively, if there is a new proton interaction process which becomes important at $\sim 10^{15}$ eV ($\sim 10^3$ GeV in the centre of mass system), several of the observed energy-dependent features of the cosmic ray beam become naturally explicable.

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