

# Fine Structure in the Energy Spectrum of Cosmic Ray Protons at 50 GeV ?

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## Abstract

The recently published precise spectrum of cosmic ray protons from the Alpha Magnetic Spectrometer has been examined in some detail from the standpoint of a search for deviations from a smooth, simple, power law. We find a significant excess ( $\simeq 10\%$  over  $\sim 0.3$  interval in  $\log E$ ) centered on 50 GeV in the published data. It is possible that the 'unfolding technique' adopted by the experimenters causes an overestimate of the excess but it is difficult to reduce it much below about ( $5 \pm 2$ )%.

We have examined other recent data, too. There is also evidence here, for an excess in the same energy region, although of only ( $1.6 \pm 0.9$ )%. A value of ( $3 \pm 1.5$ )% would be consistent with all the data. There are hints of similar excesses for heavier nuclei and electrons.

Possible explanations are put forward for an excess, should it prove to be genuine.

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## 1 Introduction

It is commonly asserted that the energy spectrum of cosmic rays is almost featureless, being characterised by a power law spectrum which slowly steepens near  $3 \cdot 10^{15}$  eV ( the knee ) and continues with a new exponent to near  $10^{19}$  eV, where it flattens somewhat ( the ankle ).

In fact, we ( Erlykin and Wolfendale, to be referred to as EW ) have claimed that near the knee the situation is more complex ( [1] and references therein ). The complexity is attributed to the effect of a single, local and recent supernova, the remnant of which has accelerated particles, particularly oxygen and iron nuclei, with a spectrum of the form  $E^{-2}$  up to a rather sharp maximum at  $\simeq 4 \cdot 10^{14} Z$  eV. It is not unreasonable, statistically [2], that such a single 'source' should show itself in a rather narrow band of energy.

## 2 The AMS experiment

The EW result has led us to examine the situation at other energies, viz. to search for irregularities. The very recent results from the powerful AMS experiment [3] make a study of the proton spectrum recorded by that experiment of considerable value, from the standpoint of small deviations from smoothness. That such irregularities cannot be more than a few tens of percent is inferred from studies of the spectra reported by earlier workers ( to be considered later ). However, the AMS ( satellite ) experiment, with its  $10^7$  particles and carefully calibrated equipment, holds out the hope of searching for irregularities down to a few percent in intensity ( over some tens of GeV ).

The AMS authors have presented data on the proton spectrum from the kinetic energy 0.1 to 200 GeV. Below about 10 GeV ( for certain directions of incidence with respect to the earth ) interesting geomagnetic effects are visible, but these are not the subject of concern here. Rather, we examine the spectra above 10 GeV where geomagnetic effects quickly become negligible. In this energy range all the data presented, which relate to 10 bands of geomagnetic latitude, are completely consistent and, when averaged by us, they give the spectrum shown in Figure 1.

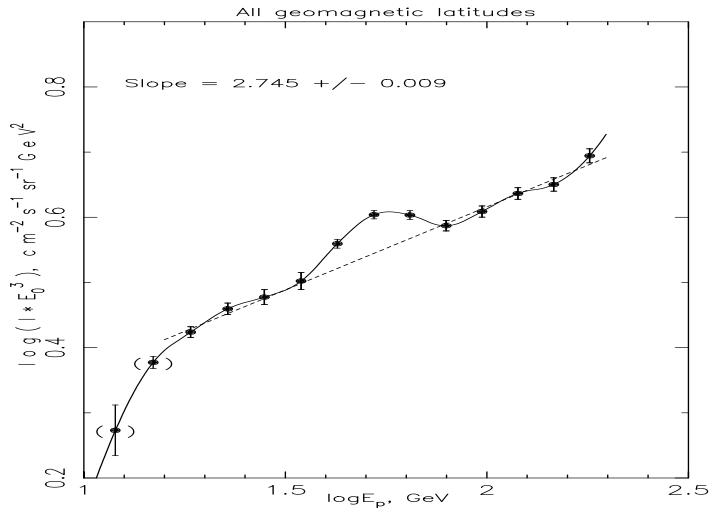


Fig. 1. The AMS primary proton energy spectrum [3] for all geomagnetic latitudes. The dashed line is the best fit of the spectrum excluding the points in brackets, and those in the  $\log E_p = 1.55 - 1.85$  interval. The errors indicated are only statistical; those in brackets are affected by geomagnetic processes. The magnitude of the excess may be too high, by a factor  $\sim 2$  for reasons to do with the corrections applied by the workers themselves ( see text ).

A discussion of the 'errors' in the intensities is necessary. In the AMS work the errors for each of the ten bands of geomagnetic latitude are enlarged considerably to allow for 'systematic errors'. Such errors are, no doubt, present,

but they should vary slowly from one energy bin to the next - viz. they should not, in themselves, be able to give the observed excess. The dispersion of the intensities ( the actual points ) about their mean ( from the averaged set of ten ) is very small indeed and the errors indicated by us in figure 1 are correspondingly small.

The result is of considerable interest in that it shows that a single power law ( shown dashed ) will not fit the data. Instead, an excess appears centered on 50 GeV. The 'peak' is some 15% above the power law of constant exponent neglecting the region of the peak.

It has been pointed out to us ( by Professor Yu.Galaktionov of the AMS group ) that the unfolding technique used to 'correct' the data may amplify existing irregularities. This is, of course, true but the fact that every one of the ten spectra presented shows such ( amplified ? ) peaks indicates, to us, that there is an underlying genuine peak. The AMS group shows, as an example, a representative spectrum before and after unfolding. We estimate that the 'raw' spectrum has an excess about one half of that after correction. It seems safer, therefore, to take this value as the AMS result, i.e.  $\sim 6\%$  above the power law.

In Figure 2 we give the excess from a datum line which is drawn through intensities in the range  $\log E = 1.20 - 1.55$  and  $1.85$  onwards, the intensities below  $\log E = 1.20$  are increasingly affected by geomagnetic processes and are not used. An important point about taking excesses from such a datum is that the slowly varying systematic errors disappear on subtraction. Thus, the only errors left in the AMS excesses of Figure 2 should be the, presumably smaller, rapidly varying systematic errors. As remarked above, such errors due to the unfolding technique probably reduce the AMS values by a factor 2, to give the line as shown dashed in the Figure.

Returning to the initial excess, the peak carries with it  $\sim 2 \cdot 10^{-3}$  eV cm $^{-3}$ , i.e. 0.4% of the total cosmic ray energy density; the reduced value is, correspondingly,  $\simeq 1 \cdot 10^{-3}$  eV cm $^{-3}$ .

An interesting feature is that the peak is rather narrow, being not far from what would have been expected from the momentum resolution of the instrument itself.

### 3 Comparison with the Results of Other Workers

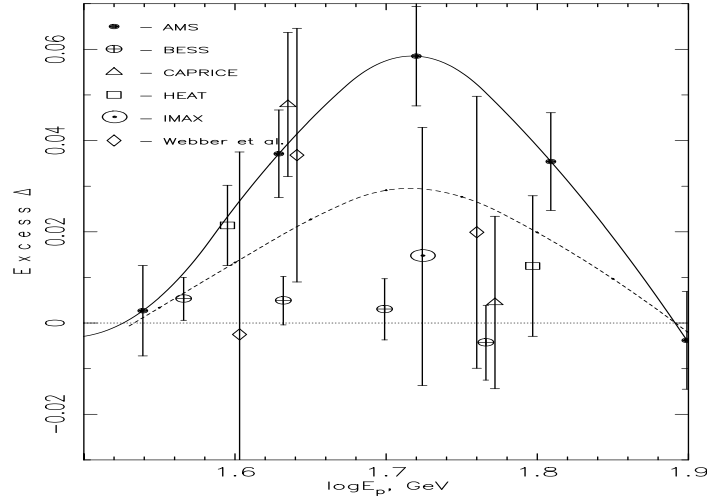


Fig. 2. Excess of the primary proton intensities over the best fit straight line: ● - AMS [3], ⊕ - BESS [4], △ - CAPRICE [5], □ - HEAT [6], ⊙ - IMAX [7], ◇ - Webber et al. [8]

### 3.1 Results for Protons.

It is necessary to examine the extent to which the AMS 'excess' is also found in those other experiments in which the proton spectrum has been measured. Clearly, despite the undoubted superiority of the AMS project ( in terms of particle numbers, at least ), it is necessary to have support from other work, or at least reasons why others did not see the excess, before taking the excess seriously.

Figure 2 shows the excess intensities derived by us from the data. The logic in drawing a straight line for the datum needs consideration, the main reason is that this is standard procedure as a way of quantifying the spectral shape. There might, in fact, be some very small curvature ( convex upwards ), but due to small residual solar curvature and the narrow interval,  $\sim 1.2/2.4$ , where the excess was derived, the overestimate of the excess cannot exceed 0.003.

### 3.2 The Results for Heavier Nuclei.

The fraction of nuclei in the cosmic radiation falls with increasing  $Z$  and the statistical accuracy falls accordingly. The search for fine structure is, correspondingly, even more difficult than for protons. Nevertheless, a search has been made.

A useful summary [9] has been given for the spectra of P, He, C, O, Mg, Si and Fe in terms of rigidity. Such a parameter is important in view of the fact that

a promising explanation for the proton structure is in terms of acceleration effects by way of weak SNR in the ISM ( see §5 ) and these will presumably be rigidity-dependent. Inspection of a superposition of the rigidity spectra over the range 100 - 200 GV reveals no peak at 50 GV ( specifically  $\Delta \leq 0.05$ , but perhaps a peak at twice this rigidity:  $\Delta = 0.07 \pm 0.05$  at 100GV.

Comparison with Figure 2 shows that the 50GV upper limit is a little above the 'corrected' AMS value (  $\Delta \simeq 0.03$  ) and thus not inconsistent with it. However, it gives no positive support to the proton results.

Turning to 100 GV rigidity ( 100 GeV energy for protons ) inspection of Figure 1 shows a peak there of less than about 0.01, not inconsistent with the  $0.07 \pm 0.05$  for the heavy nuclei, but again not providing positive support. It should be remarked, however, that 100 GeV is getting close to the 'maximum detectable energy' of the AMS spectrometer, and peaks would certainly be smeared here and their magnitude considerably reduced.

### 3.3 *The Results for Electrons.*

It is here that recent work [10] gives rather strong evidence for a peak at 50 GeV, of magnitude  $\Delta = 0.27 \pm 0.1$ . The only other experiments of adequate statistical precision give a broad peak in the same region of smaller magnitude: in one case  $0.1 \pm 0.1$  [11] and a null result in the other:  $0 \pm 0.1$  [12], the last-mentioned being a measurement reported 24 years ago. The average is  $\Delta = 0.10 \pm 0.06$ .

## 4 Discussion of the results

Taking the AMS results at their face value the 15% excess in the peak reduces to  $(11 \pm 1.5)\%$  when averaged over the range  $\log E$ : 1.55 - 1.85. However, as remarked earlier, a safer estimate is lower by a factor  $\sim 2$ , with a larger error; specifically the 'best estimate' for the average is  $(5 \pm 2)\%$ .

Turning to the mean of the other results, this is  $(1.6 \pm 0.9)\%$ , a value lower than our AMS value but not impossibly so. A figure of  $(3 \pm 1.5)\%$  would be consistent with both.

Turning to the results for other components, and transforming from  $\Delta$ -values to percentages, we have:

- nuclei of the same rigidity:  $< 12\%$
- electrons of the same rigidity ( and energy ):  $26 \pm 16\%$

The results for nuclei are not inconsistent with the proton results and the electron 'peak' is, if anything, higher. Taken with the 100 GV nuclear excess ( of  $17 \pm 12\%$  ) there is at least the suggestion of small peaks in the other components, too.

## 5 Possible explanations

A non-exhaustive list is as follows.

(i) *Technical origin*

It is unlikely that technical factors, such as errors in exposure at the energy in question, are responsible for the excess in *all* the measurements, but technical causes cannot be ruled out.

(ii) *Protons from exotic processes*

Concerning the AMS excess the easiest ( observationally ) explanation would be a delta-function, i.e. the presence of protons of unique energy near 50 GeV. Apart from the large energy density ( 0.2-0.4% of the whole cosmic ray energy density ) the absence of anti-protons of the same flux ( at least none have been reported ) acts against some exotic processes, such as the decay of massive baryons and anti-baryons, at least.

Other possibilities involve the annihilation of dark matter particles of supersymmetric type [13]. Again, the non-observation of accompanying particles - such as gamma rays - rules out many possibilities. Nevertheless, there *may* be appropriate decay modes which would be acceptable. This aspect is, in fact, topical because of the possibility of dark matter candidates having the appropriate mass.

(iii) *Supernova Remnant Effects*

Although not predicted by acceleration models, such as was - in a sense - the situation for the EW mechanism at PeV energies, this is perhaps the best contender. The stochastic nature of supernova shocks means that there *must* be spectral structure at some, small, level, at all energies where supernovae play a part. We are currently examining this aspect in some detail.

The likely presence of small effects for the spectra of nuclei and electrons increases the attractiveness of this interpretation.

(iv) *Heliospheric Shock Effects*

The energy in question, 50 GeV, is of the right order to be possibly accommodated by shocks at the heliospheric boundary. However, why the excess should be so sharp ( after allowance for resolution broadening ) is a mystery.

## 6 Conclusions

Inspection of the very recent, precise, AMS measurements of the primary cosmic ray proton spectrum shows an interesting excess in the region of 50 GeV. Although the quoted values may overestimate the excess - perhaps by a factor 2 - it seems unlikely that the whole effect will go away.

Including results from other proton experiments, too, an overall excess averaged over  $\Delta \log E = 0.15$  centred on 50 GeV of  $(3 \pm 1.5)\%$  would fit all the data.

It should be possible to confirm or deny a value of this magnitude by a more sophisticated study of the AMS results.

More importantly, perhaps, is the general point that modern experiments of apparently high precision, should focus on examinations of the detailed shape of the energy spectrum of protons, of heavier nuclei and of electrons, too. Fine structure should be visible at some level; perhaps it is already starting to be seen ?

Concerning the explanation, if the heavier nuclei do, in fact, show similar effects to those for protons ( at present the results are clearly very marginal ) - at the same rigidity - it will be possible to rule out exotic processes as being responsible. Weak, local supernova remnants, would then be the preferred mechanism. However, it is premature to rule out exotic processes, yet.

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