Fine structure in cosmic ray spectra.

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Abstract. The case is made for there being more 'structure' in the cosmic ray energy spectra than just the well-known knee at several PeV and the ankle at several EeV. Specifically, there seems to be a 'dip' or 'kink' at about 100 GeV/nucleon, a possible 'bump' at about 10 TeV, an 'iron peak' at 60 PeV and the possibility of further structure before the ankle is reached. The significance of the structures will be assessed.

1. Introduction.

Science is littered with examples of small effects having profound consequences and the 'noise' being more important than the signal. The discovery of the cosmic microwave background is one example, that of cosmic rays is another. In the cosmic ray case the ensuing measurement of the energy spectrum of the particles seemed to indicate a rather featureless form of rapidly falling intensity with increasing energy. From the 1950s onwards it was realised that there were two features in the energy spectrum: a 'knee' at several PeV and an 'ankle' at several EeV. Many still subscribe to this view but we contend that there is more structure in the spectrum (and for electrons and gamma rays, too) and that the structure is giving guidance as to the origin(s) of cosmic rays (CR).

In our view, the situation resembles that in the history of optical spectra. Thus, the continuum was understood by the Indian Vedics in the 15th Century - and explained by Newton in the 18th. 'Fine Structure' was first observed by Bunsen and Kirchoff in the 19th Century and its role in studies of the atom is well known. Hyperfine structure dates from Michelson in 1881 and it was eventually realised that properties of the atomic nucleus were involved.

We consider that in cosmic rays we are at the start of the 'fine structure' period.

2. The knee.

Everyone agrees that there is a knee, ie a steepening of the energy spectrum of nuclear CR, but there are arguments as to its origin. Our own view, expressed in many publications (starting with Erlykin and Wolfendale, 1997) is that its' sharpness indicates that it is caused, largely, by an underlying sharp 'peak' (on a plot of $E^3I(E)$ vs E) due to a single supernova remnant. This is our 'Single Source Model', SSM. We have made the case for the knee being due mainly to helium (following observations by KASCADE, eg Apel et al., 2009) but we have also presented evidence for an 'iron peak' at an energy of about 60 PeV (see Erlykin and Wolfendale, 2011 for a summary of recent work involving the iron peak).

Figure 1 summarises the situation, the caption providing the details.
Figure 1. A summary of evidence for fine structure of cosmic ray spectra in the knee region. The data come from all available Extensive Air Shower experiments. The patterns are normalised to the position of the knee in either shower size, N, or energy, E. The sharpness is the second differential of the logarithm of \( N^3 I(N) \) vs \( \log N \). The 'excess' is the deviation of the intensity for each point from the running mean. The data represent a world summary from our analyses, by way of Erlykin and Wolfendale, 1997 to Erlykin and Wolfendale, 2012.

A: dip below the He peak, B.
C: peak due to CNO
D: dip before the iron peak, E.
It is tempting to identify the knee and the iron peak (with perhaps CNO in between) as being due to particles from the same local SNR insofar as their energies are approximately proportional to Z. We have tentatively identified MONOGEM as the source (Erlykin and Wolfendale, 2004) but the VELA pulsar cannot be ruled out.

The crucial observational facts about the knee and the iron peak are their ‘sharpness’; we contend that they are both so sharp as to need just one source to have been responsible. If many SNR were to contribute, then their inherently different maximum energies, caused by differing ISM densities, magnetic fields, intrinsic total energies etc, would cause an unacceptable blurring of the spectrum in the knee region. There is, of course, an underlying near continuum of ‘background’ particles coming from many SNR further away and/or older.

3. The ankle.
The second feature to have been discovered is the ankle as several EeV. Figure 2 shows this feature.

Our long-held contention is that it represents the transition from Galactic to Extragalactic (EG) particles (eg Wibig and Wolfendale, 2005)

Indeed, it looks to be so sharp as to demand rapidly falling and rapidly rising components. A model in which the Galactic component at the highest energies was mainly iron would give a satisfactory explanation in that (super?) SNR could give iron nuclei up to the EeV region. The EG nuclei could be of any mass, although many years ago it was suggested that heavy nuclei might predominate here, too, eg Tkaczyk et al., (1975). The advantage of heavy nuclei is two-fold:

a. most acceleration processes give maximum energies proportional to Z, and
b. the near-isotropy of arrival directions is explained more easily: the particle trajectories will be more randomised by the tangled magnetic field in the inter-galactic medium.

Unfortunately, iron nuclei have not been confirmed in the EeV region, light nuclei being preferred, the measurements from different experiments showing a remarkable, and worrying, spread of values and the subject is open. The EG particles too have not been unambiguously identified, with, for example, the PAO (Abraham et al., 2009) preferring the heavies and HiRes (Abbasi et al, 2005) preferring the light nuclei. It is not impossible that there is a change in the character of nuclear interactions post LHC energies, that would rectify the problems, although it is premature yet to claim such a change.

Another possibility is that the EG particles (which can be light nuclei) ‘take over’ in the 100s of PeV region and that the ankle is caused by p-CMB interactions (Berezinsky et al., 2004) but we (Wibig and Wolfendale, 2005) claim that the ensuing ankle would not be sharp enough.

What is clear is that there is structure providing the ankle, it is largely the differences in the experimental results that prevent an explanation.

4. The kink.
There is evidence for a kink in the spectrum of all nuclei at about 200 GeV/nucleon (PAMELA; Adriani et al., 2011; ATIC, Panov et al., 2009; CREAM, Ahn et al., 2009, 2010; Yoon et al., 2011).

Figure 3 shows an example for protons and the He nuclei. We (Erlykin and Wolfendale, 2012) have explained it in terms of a ‘new component’, perhaps associated with the Local Bubble. The case can also be made for a similar kink in the electron spectrum of the ATIC experiment (Adriani et al., 2011); again, a New Component has been invoked by us (Erlykin and Wolfendale, 2012).

In fact, structure in the electron spectrum - arising from discrete local sources - has long been expected (Kobayashi et al., 1999; Erlykin and Wolfendale, 2002) the reason being the limited
Figure 2. The ankle, after Wibig and Wolfendale (2005). The points represent a world survey. Although there is a spread outside the quoted errors most experiments individually give a sharp ankle. The lines represent our preferred Galactic (left) and Extragalactic (right) spectra. In (a) and (b) the data are normalised to the same ankle energy and the mean intensity taken. The points in (a) represent the mean of consecutive pairs in (b).

collection volume for electrons because of their limited lifetime due to energy-dependent energy losses.

The FERMI-LAT results (Strong et al., 2011) on diffuse gamma rays also appears to show a kink, but at \( \sim 10 \) GeV (Erlykin and Wolfendale, 2011b)

5. The ‘bump’.
There is no limit to the possibilities for structure of a rather smooth type in the CR spectra. Our calculations (Erlykin and Wolfendale, 2003) in which propagation from random SNR in the Galaxy (following their known radial distribution) to the solar system was considered give spectra with a variety of ‘curvatures’. It is possible that the recent ‘bump’ in the CR spectrum
Figure 3. The ‘kink’ in the Proton (P) and Helium (He) spectra from PAMELA (Adriani et al, 2010) ATIC (Panov et al., 2009) and CREAM (Ahn et al., 2009; 2010; Yoon et al., 2011). The lines are drawn by us to represent a power law ‘background’ and a steeply falling new component, denoted NC.

observed by ‘CREAM’ (Maestro et al., 2010) near 1 TeV is an example of this type. In any event, there should be ‘bumps’ in the various spectra of a variety of magnitudes (of height and energy extent ) and their frequency should increase with energy.

Interestingly, the energy dependence of such bumps differs between the predictions for Normal and Anomalous diffusion (Erlykin and Wolfendale, 2003). This fact arises because of the differing spatial extent of the particles arising from a particular source in the two cases. This feature might prove to be a diagnostic for the yet unresolved problem of the manner of CR diffusion.

6. Conclusions.
The case has been made for a variety of ‘fine structure’ features in the cosmic ray spectra. Those below 100 PeV we interpret in terms of the effect of local SNR, that above 1 EeV is although sharply defined, of uncertain origin.

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