Structures in the cosmic ray energy spectra

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Abstract

All the components of Cosmic Rays (CR) have ‘structure’ in their energy spectra at some level, ie deviations from a simple power law, and their examination is relevant to the origin of the particles. Emphasis, here, is placed on the large-scale structures in the spectra of nuclei (the ‘knee’ at about 3 PeV), that of electrons plus positrons (a shallow ‘upturn’ at about 100 GeV) and the positron to electron plus positron ratio (an upturn starting at about 5 GeV).

Fine structure is defined as deviations from the smooth spectra which already allow for the large-scale structure. Search for the fine structure has been performed in the precise data on positron to electron plus positron ratio measured by the AMS-02 experiment. Although no fine structure is indicated, it could in fact be present at the few percent level.

1 Introduction

Starting with the ‘all-particle spectrum’ it has been known for many decades that a simple power law does not represent the spectrum, rather, the power law exponent increases at several PeV (the ‘knee’) and falls again at several EeV (the ‘ankle’). Both have been examined in great detail, but without a concensus as to their detailed origin. Here, as for the all-particle spectrum, we restrict attention to the knee and its’ apparent ‘sharpness’.

Turning to electrons, their energy spectrum has a distinctive shape, with increasing agreement that, when plotted as $\log E^3$ vs $\log E$, there is a flattening at about 100 GeV and a downturn commencing at about 1000 GeV. Interest centres on the role of a single source, a pleasing result in view of the lukewarm reaction to our early ‘Single Source Model’ for the knee \cite{1}. Surely, the single source responsible for the flattening in the electron plus positron spectrum has to be different from that responsible for the knee, but the principle is the same: a single source is providing structure.

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Finally, with respect to positrons, a number of observations have reported an upturn in the positron fraction (the number of positrons divided by that of electrons plus positrons), starting at about 5 GeV \[2, 3, 4, 5, 6\]. The comprehensive list of references can be found in the review \[7\]. The case here for a local source providing the extra positrons seems overwhelming. In each case, we wish to work out the probability that a single source (SNR) can produce the observed feature, or one that is at least as 'dramatic'. A small value of the probability will indicate the unlikelihood of this explanation and a large value, say bigger than a few tens of percent, will give confidence. A related analysis will also be made of techniques for determining to what extent very precise measurements of apparently smooth energy spectra can give information about the origin and propagation of the particles.

2 Large-scale structures in the Cosmic Ray Energy Spectra

2.1 The knee in the all-particle spectrum

In view of its' history (it was discovered in 1958 \[8\]) this feature is the most studied. In our detailed analysis using the developed SNR model \[9\], a model in which the standard Fermi acceleration mechanism was used for acceleration by the SNR shock, we derived the age-distance diagram for the SNR which could be responsible for the formation of the knee, ie our 'single source' \[10\]. The 95% confidence level encompassed distance: 250 to 400 pc and age: 85 to 115 ky. Surprisingly, perhaps, the area occupied by the age-distance contours for an SNR giving a knee sharper, or more pronounced, than that observed is not much bigger than this, assuming that the energy injected by the SNR into CR is the standard \(10^{50}\) erg. The mean number of SNR expected in the required age-distance region is about 0.01-0.02, ie the probability to find SNR within this region, which gives the sharp knee-like structure, is about 2%.

If we relax the requirement of the sharpness and look for somewhat smoother deviations from the simple power law then the examination of simulated spectra presented in \[11\] (anomalous diffusion with \(\alpha = 1\)) gives the probability of such features of about 28%. In view of the difficulty in both measuring the knee and in interpreting it (diffusion characteristics, etc) we see no reason to doubt the conclusion that a single source is responsible.

2.2 The electron component

In \[12\] we presented a model in which, as for protons, electrons are accelerated by the shock in the SNR, the SNR then being distributed in the Galaxy randomly in space and time. The well-known steeper energy spectrum for electrons than for protons was explained by way of an energy-dependent Mach number for the shock. It must be remarked, however, that this feature is not yet fully understood.

Inspection of our model's prediction for the shape of the electron energy spectrum \[12\] shows a wide range of spectra with a median intensity \((\log IE^3)\) which falls slowly
with energy to about 100 GeV, beyond which it falls rapidly. This is in contrast with
the observed electron plus positron spectrum which rises slightly or flattens at about
100 GeV and falls with modest rapidity above 1000 GeV. It should be noted that the
ATIC spectrum \[3\] has remarkable structure in the range 100 to 1000 GeV, but this is
not shared by other measurements, eg Fermi LAT \[5\]. Examination of \[12\] indicates that
about 24% of the predicted spectra have the necessary or stronger large-scale spectral
structures.

### 2.3 The positron fraction

A number of experiments have shown an upturn in the positron fraction, as mentioned
already. The most precise are due to: PAMELA \[2\], Fermi-LAT \[5\] and AMS-02 \[6\].
Many authors have suggested that a pulsar is responsible, but, in a very recent work
\[13\], we have proposed the SNR presumed to be the predecessor of the pulsar Geminga.
In this case, the positrons come from radioactive ejecta from the SN; the positrons are
then accelerated by the SNR shock in the usual way. An advantage of this mechanism
is that the acceleration efficiency of the near-1 MeV positrons is very high.

In a manner similar to that for the origin of the knee ( §2.1), we have determined
the limits on distance \( D \) and age \( T \): \( 250 < D < 320 \) pc and \( 170 < T < 380 \) kyear. The
mean number of SN explosions expected in this age-distance range is about 0.3 and
the probability of just a single occurrence according to the Poisson distribution is about
22% which is not an unreasonable value. Eventual measurements of the anisotropy of
electron and positron arrival directions will show whether, or not, the identification is
correct.

### 2.4 Anti-protons

If anti-protons are generated and accelerated in SNR, by the interactions of protons
and heavier nuclei with the interstellar medium (ISM) within the remnant, then their
spectrum should show large-scale structure, in the form of an upturn in the \( \bar{p}/p \) ratio.
Interestingly, neutrons produced in \( \bar{n}, n \) - pairs in the interactions will augment the \( \bar{p} \)
flux. The neutrons (and \( \bar{n} \)) have the advantage of escaping the magnetic trapping,
which may be strong in the early remnant, before decaying into \( p \) and \( \bar{p} \).

The only measurements extending as far as hundreds of GeV are those from PAMELA
\[14\], which finish at 180 GeV, although the errors are large at the high energies. The
measured ratio at 100 GeV is \((1.7 \pm 0.5 \cdot 10^{-4})\), but this includes a rather uncertain
background contribution \[14\] so that a single source contribution, or upturn in the ratio,
cannot yet be determined. All that can be said at present is that the \( \bar{p}/p \) ratio hints
at a flattening above 10 GeV, which, if confirmed and after subtraction of the rapidly
falling background and accounting for a steep proton spectrum in the denominator of
\( \bar{p}/p \) ratio, would suggest the onset of a finite single source contribution.

Its absence would suggest that \( \bar{p} \) are not produced by the local SNR, unlike the
positrons which we hypothesise to come from the radioactive SN ejecta. At present the
expected 'cross-over energy', where SNR-generated \( \bar{p} \) equal background, is not clear.
3 Fine Structure in the Positron Fraction

3.1 Search for fine structure

By 'fine' rather than 'large-scale' structure we mean anything in the spectrum, or particle (positron) fraction, that is over and above the first order fit, suggested by the AMS-02 collaboration [6]. This fit was the sum of two simple expressions: a power law for those positrons coming largely from CR interactions in the ISM and an exponentially modified power law for positrons from a local source. The energy range is from 1 to 300 GeV, i.e. $\log E, \text{GeV}: 0$ to 2.5. Below 10 GeV, solar modulation is important and thus we divide the data into two parts: $\log E, \text{GeV} = 0$ to 1.25 and $\log E, \text{GeV} = 1.25$ to 2.5. The lower part might show fine structure due largely to solar modulation, whereas the higher energy part might indicate Galactic effects, associated with the finite number of sources contributing to the CR flux.

In an attempt to determine at least an upper limit to the fine structure in the positron fraction we have examined the 'precise' AMS-02 data in some detail, as follows. Fits to the ratio of the measured positron fraction to that obtained by its fit with the AMS-02 suggested function were made for the two halves of the data for various degrees of polynomial function 'n' from 2 to 9 with particular emphasis on 2 and 9 themselves. Thus, we are searching for fine structure within the already allowed - for large-scale structure. Clearly, it will be small, otherwise it would have been commented on already.

![Figure 1](image-url)

Figure 1: The ratio of the positron fraction measured in the AMS-02 experiment to its fit by the AMS-02 suggested function. Errors of the ratio are statistical. Full lines in both halves of the energy range show the weighted fit of the ratio by the 2-degree polynomial function: $a_0 + a_1 X + a_2 X^2$, where $X = \log E$. The quality of the fit is shown by the values of the reduced $\chi^2$. Dashed lines indicate the structure, which is of the same shape of the 2-degree polynomial, but has $P(\chi^2) = 0.05$.

Figure 1 shows the results for $n = 2$ (full lines) and the derived chi-square value with its’ significance for both halves of the studied energy range. Indicated errors of the
ratio are statistical. Systematic errors are weakly energy dependent and cannot have irregular behaviour with the energy. In this analysis we did not take them into account since they cannot help to reveal the possible fine structure of the energy spectra.

The weighted polynomial best-fit has a reasonable significance at lower energies and the very large value of the probability at high energies indicates that even the statistical errors shown may have been overestimated. The limit for a 5% probability of fit is shown by the dashed lines. The 5% level is the usual value for acceptance of a fit as being just non-allowable. It will be noted that the 'fine structure' of this shape could reach about 8% maximum at least in the high energy part of the range and still not be dis-allowed by the data. We presented these dashed lines just as examples illustrating the non-negligible probability of deviations from the AMS-02 fit at the level of the few percent.

Figure 2 shows the situation for $n = 9$. The best-fit has again a very high probability in both halves of the range. This fit has some interesting features although none is as yet significant. The 5% probability limits are shown by the dashed lines. They show that the amplitude of 'undulations' in some restricted regions are still allowed to be as high as 17% by the data. Again the dashed lines here are given as possible examples of the fit which still have the allowable probability.

Figure 2: The same as in Figure 1, but the ratio is fitted by the 9-degree polynomial function. The position of the minimum in the ATIC electron plus positron energy spectrum is indicated by the arrow. Its approximate coincidence with the upward excursion of the positron fraction from the regular model calculation is an interesting feature. However, due to the low statistics, it should be regarded rather as a hint for the possible fine structure.

3.2 Discussion of possible sources of fine structure

3.2.1 Solar wind modulations

As remarked already, the lower energy region is the province of solar modulation, which is known to be dependent on the charge sign of the CR and on the time of observation,
by way of the solar magnetic field polarity [eg 15]. The difference between the positron fraction measured by AMS-01 [16] and PAMELA [2] in the different periods of solar activity can be caused by this phenomenon [7].

Although precise measurements of AMS-02 in the lower energy region are quite consistent with their fit by two-term function (background plus single source, $\chi^2/ndf = 28.66/31$, $P(\chi^2) = 0.586$) it is worth-while to estimate the upper limits of the possible fine structure consistent with these measurements. As can be seen in Figure 1 the maximum contribution of the 2-degree polynomial-like structure which still has the 5% confidence level of consistency with data points is about 0.011. The same estimate for the narrower structures which appear in the 9-degree polynomial fit gives a maximum contribution of only 0.035.

It is seen that the present high precision measurements does not allow the presence of fine structure greater than about 3-4% in the GeV energy region due to solar wind modulation. Later measurements should be of adequate accuracy to enable the effect of time-dependent modulation to be studied, using factors such as those in [17].

3.2.2 Galactic source modulations

We now discuss the higher energy region. It is here that the ATIC results [3] have relevance, in that the measured electron plus positron spectrum has considerable structure. The energy of about 220 GeV at which an apparent minimum in the electron + positron intensities appeared is indicated in Figure 2. It would have been expected that, if positrons were uncorrelated, there would have been a maximum at this energy in the positron fraction. However, statistical errors of the measured positron fraction are too high to confirm the anti-correlation between the ATIC minimum of the electron plus positron intensity and the AMS-02 maximum of the positron fraction. Other ATIC minima are at higher energies which do not overlap with the range of AMS-02 measurements.

3.2.3 Spectral structure as a diagnostic of CR origin

Both SNR and pulsars are candidates for CR origin and a distinction between them is not a trivial problem. However, spectral structure (or fine structure) can be useful, particularly for the electron component which, because of energy losses, comes predominantly from 'local' regions (within a kpc or so) and thus from a smaller number of CR sources.

A comparison can be made between our electron spectra from the random SNR model [12] and the prediction for pulsars [7, 18]. It is immediately apparent that the prediction for SNR are 'smoother' than those for pulsars. Over the range 100-2000 GeV, the SNR model has rarely excursions in 'intensity' ($\log IE^3$) bigger than 30% whereas for pulsars there are four excursions with a mean of 40%.

The reason for the difference is self-evident. For SNR, in the model, at least, unique energy spectra are emitted from the SNR when the SNR 'bubble' bursts, and the spectral structure arises from propagation effects alone, i.e. contributions from SNR of different ages at different distances. For pulsars, the flatter 'emission spectra' have
maximum energies depending on their ages, with, conventionally, sharp cut-offs, and these fluctuations are added to those due to propagation.

Comparing the structure for electrons and protons, it is useful to examine the range of intensities as a function of energy (for the same propagation model) from our work [11][12], which relates to 50 independent samples. A large range suggests more structure than is the case for a small range. It is found that the ranges for electrons and protons are similar to about 1000 GeV, above which the range for electrons increases more rapidly. A similar result is apparent for the degree of ‘oscillation’ of the spectra—that for electrons is singularly large in the next decade of energy. However, the ‘degree’ of oscillation is hard to quantify and this is why the range of intensities is considered. This behaviour follows from the fact that electron losses increase as the energy squared and the transit time from source to observer; the actual spatial and temporal distribution of nearby sources is therefore critical.

4 Conclusion

We have analysed the available results on the energy spectra of CR particles from the standpoint of the ‘structures’ in their energy spectra. Large-scale structures are regarded as differences from simple forms, which point to the existence of a single SNR. The model adopted is that introduced by us [11][12] involving CR origin from randomly situated SNR from which CR diffuse. The probability of seeing such structure is $\sim 30\%$ for nuclei, $\sim 20\%$ for electrons and positrons. For anti-protons, measurements cease at the energy at which structure might be expected to show itself; more extended measurements might show an upturn in the $\bar{p}/p$ ratio.

Fine structure is defined as deviations from the smooth spectra which already allow for the large-scale (single source) structure. The precise positron fraction data [6] are taken as an example. The datum is taken as the two components: background plus single source. The polynomial fits are taken as examples: $n = 2$ and $n = 9$, and the data are divided into equal energy ranges: $\log E, \text{GeV} = 0 - 1.25$ and $1.25 - 2.50$. Although no fine structure is indicated, it could be present at the few percent level. For the lower energy band solar modulation effects, which are charge dependent, should be detectable when temporal and somewhat better statistical data are available.

For the higher energy range, models are not yet available for the fine structure expected as a result of detailed source mechanisms (eg SNR or pulsars) and irregularities of CR diffusion, but these will come. Again, although the positron fraction data are statistically precise, fine structure could be present at a few percent level (up to 8% for $n = 2$ and up to 17% for $n = 9$ as an example).

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