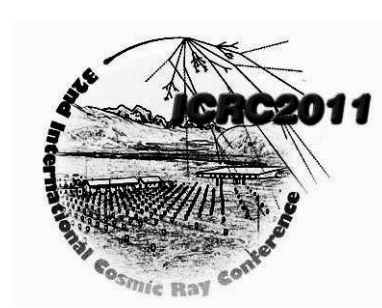


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## A New Component of Cosmic Rays?

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**Abstract:** Recent direct measurements of the energy spectra of the major mass components of cosmic rays have indicated the presence of an 'ankle' in the region of 200 GeV per nucleon. The ankle, which varies in magnitude from one element to another, is much sharper than predicted by our cosmic ray origin model in which supernova remnants are responsible for cosmic ray acceleration and it appears as though a new, steeper component is responsible.

The component amounts to about 20 percent of the total at 30 GeV/nucleon for protons and helium nuclei and its magnitude varies with nuclear charge; the unweighted fraction for all cosmic rays being 36%.

The origin of the new component is subject to doubt but the contenders include O, B, A, supergiant and Wolf-Rayet stars, by way of their intense stellar winds. Another explanation is also in terms of these particles as the sources but then being trapped, and even further accelerated, in the Local Bubble.

**Keywords:** Cosmic rays, new component, fine structure.

## 1 Introduction

It is inevitable that, as the accuracy of measurements of the energy spectra of cosmic rays has increased, further structure should be resolved which, in turn, should throw light on the origin problem.

The new measurements to be studied comprise the results of satellite- and balloon-borne detectors of increasing size and complexity. Some of the most recent cover several decades of energy, with high statistical precision, and are thus of value for the analysis of structure.

The present work is preliminary, in the sense that only limited aspects of the results are considered, and the interpretation is 'broad brush'. If our contention for an extrinsic origin of the ankles identified in the spectra is correct, and a new component is really present, the consequences for many CR processes could be considerable. The work is similar to that of Zatsepin and Sokolskaya (2006), who invoked a 3-component model for CR spectra and attributed the component below about 250 GeV/nucleon to novae. However, there are important differences, as will be seen.

## 2 Analysis of the Energy Spectra

### 2.1 Results for Protons and Helium Nuclei.

The data considered here are mainly from 3 detectors: ATIC (Panov et al., 2006, 2009), PAMELA (Adriani et al., 2011) and CREAM (Ahn et al., 2009, 2010; Yoon

et al., 2011). In our analysis it was assumed that the measured intensities were equally valid within the errors (clearly, unknown systematic errors could not be included). A 5-parameter fit of the type introduced by Ter-Antonyan and Haroyan (2000) ( hereafter T-H ) was adopted. This fit yields the normalization constant, two exponents ( $\gamma$ -values): one before the ankle ( $\gamma_1$ ) and one after ( $\gamma_2 = \gamma_1 - \Delta\gamma$ ), together with the sharpness,  $S$  and energy  $E_a$  of the ankle.

Figure 1 shows the spectra of protons and helium nuclei with the values for the parameters:  $\gamma_1$ ,  $\gamma_2$  and the energy  $E_a$  at which the ankle occurs. We assumed that the 'background spectrum' is that with slope  $\gamma_2$  extrapolated back to lower energies with a minor correction for the rigidity dependent solar modulation. The subtraction of background spectra from the total intensity of protons or helium nuclei gives the spectra of these particles for the new component, 'NC'. The fraction  $f_{30}$  is the ratio of NC/total for the given mass at 30 GeV/nucleon.

### 2.2 Results for nuclei with $Z > 2$ .

Ahn et al. (2010) have summarised the results from all the available experiments for all nuclei. We have determined weighted mean spectra for each of the elements and performed similar analyses to those for P and He. See Figures 2 and 3.

## 2.3 Discussion of the Results.

### 2.3.1 The sharpness of the ankle.

The  $S$ -values for sharpness are crucial to the argument. Inspection of Figure 3 shows that although the errors on  $S$  are large, there is no doubt that the mean is 'high'; approximately unity. In this connection they are bigger than expected from the values from the 'natural' curvature of the spectra expected from our random supernova model (Erylykin and Wolfendale, 2003, 2011) from which  $S$ -values of less than 0.1 are expected. The probability distribution of the  $S$ -values from the random SN model is indicated. The values expected are very small because the predicted spectra are very smooth.

It is self-evident that the ankle is sharper than those from the random SN model and its explanation is terms of a new component seems assured. Possible origins will be given later.

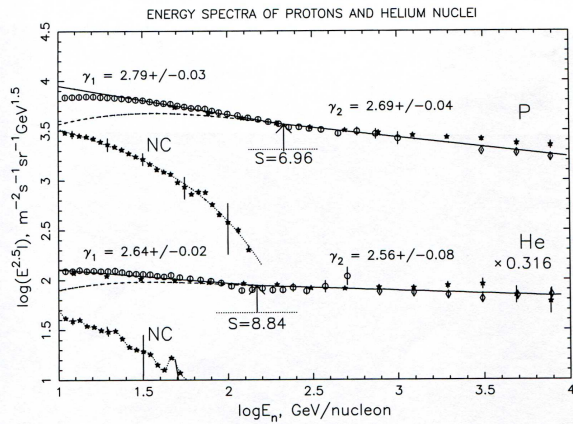


Figure 1: Proton and Helium spectra and the derived 'new component', NC. Arrows indicate positions of the ankles, attached dotted lines show their uncertainties. 'S' is the sharpness of the ankle given by the T-H formula. The  $S$  values are given for completeness; their uncertainties are difficult to estimate but the fact that the values are always large demonstrates that the ankles are sharp. Figure 3 gives more conventional estimates.

Protons. Key to symbols: circles-PAMELA, diamonds-CREAM, stars-ATIC (references in the text). Full lines - fit with the T-H formula. Dashed line - extrapolation of the fit obtained above the ankle (power law with the exponent  $\gamma_2$ ) to the low energy region below the ankle. The curvature below  $\log E_n = 2$  is due to allowance for solar modulation (using the analysis of Berezhko and Ksenofontov, 1999). Stars show the spectrum of the 'New Component' (denoted as NC). Dotted line drawn through the stars - the fit of NC with an expression (1).

Helium. As for protons. The correction for solar modulation, which is dependent on rigidity, is smaller for helium than for protons at the same energy/nucleon. The intensities have been multiplied by 0.316.

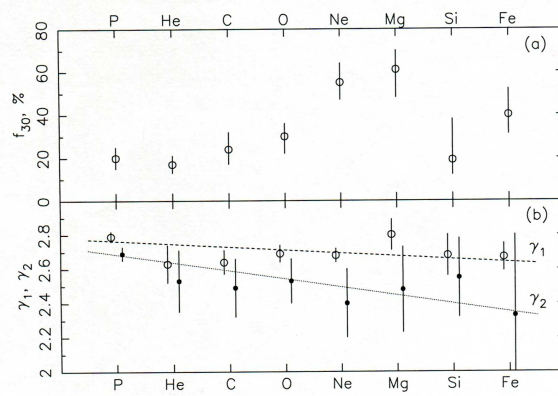


Figure 2: (a) The values of  $f_{30}$ , the ratio of the NC intensity to the total at 30 GeV/nucleon, for the various elements. (b) The slopes before and after the ankle are  $\gamma_1$  and  $\gamma_2$ . The lines are drawn for illustration purposes only, as the values for the elements are spaced uniformly.

### 2.3.2 The Energy Spectrum of the New Component

The proton spectrum, at least, has intensities of sufficient precision to allow the determination of the energy spectrum of the New Component (Figure 1). A simple form which fits the spectrum is

$$I = AE^{-\gamma} \exp(-(E/E_1)^q) \quad (1)$$

Here the parameter  $q$  quantifies the steepness of the spectrum in the cut-off region, ie the speed of its deviation from the 'parent' power law spectrum with an exponent  $\gamma$  as the energy increases. Since we study the shape of the NC spectrum and particularly its steepness we fix the best fit values of the intensity normalisation constant  $A$  and the exponent  $\gamma$  of the 'parent' power law spectrum obtained by means of 4-free parameter  $\chi^2$ -minimisation and determined the values of cut-off energy  $E_1 = 74.4 \pm 1.3$  GeV/nucleon and the steepness parameter  $q = 1.074 \pm 0.042$ .

The results for the other nuclei are less clear cut, because of lower precision but a similar form with somewhat smaller values of  $E_1$  will fit.

The shape of the NC spectrum (equation 1) should give guidance as to its mode of production. It is immediately apparent that it does not have the sharp cut-off which characterises the single SNR spectrum adopted by us (eg Erylykin and Wolfendale, 1977), nor that from Berezhko and Ksenofontov (1999).

Taken together with the results for the mass composition of the NC, the spectral measurements, and our model, indicate that an explanation in terms of a single SNR is unlikely. Instead, the sum of previous multiple SNR (or O, B etc. stars) within the Local Bubble appears to be favoured. Here, the spectral shape would be explained as the sum of several SNR of different 'strengths' and the mass composition, with its excess of high  $Z$ -nuclei, as due to the SN

having exploded in a Z-rich environment due to the previous SN and other strong stellar activity. The excess of Ne, in terms of Wolf-Rayet stars is likely (eg Meyer and Ellison, 1999, and other workers.)

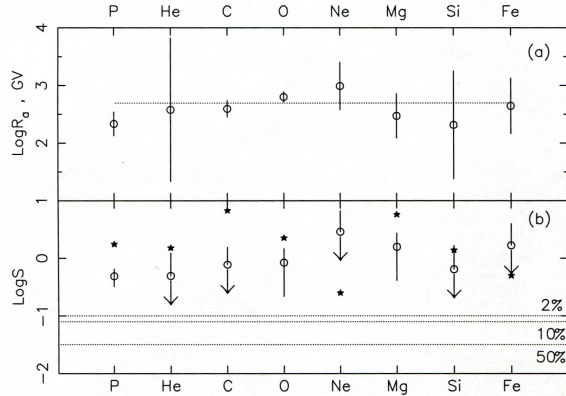


Figure 3: (a) The rigidity at the ankle ( $R_a$ ) for the various elements. (b) Sharpness values for the elements. Circles:  $S$  from use of our standard technique of the second differential of the ordinate with respect to the abscissa, with an interval of  $\delta(\log E) = 0.2$  (Erlykin and Wolfendale, 1997). Stars:  $S$  from an alternative method in which  $S = (\gamma_2 - \gamma_1)/0.2$ . The errors are given for this method. Those for the circles are similar. The horizontal lines with the percentages marked are from our random SN model (Erlykin et al., 2003). The model gives spectral profiles from which the  $S$ -values are derived.

### 2.3.3 The exponent of the 'high energy spectra', $\gamma_2$ , as a function of $Z$

The manner in which the spectral exponent varies with nuclear charge,  $Z$ , has been of interest for many years and, as the experimental precision increases, so does the interest. The analysis here appears to confirm that  $\gamma_2$  falls with increasing  $Z$ ; certainly the proton spectrum is steeper than that for He.

It is interesting to note that  $\gamma_2 = 2.56$  (assumed independent of energy) would yield a He spectrum at the knee in accord with our view (Erlykin and Wolfendale, 2011, and other workers).

The reason(s) for  $\gamma_2$  being different for protons and nuclei are somewhat beyond the scope of the present work but some remarks can be made. The reasons could be due to injection differences of differences in acceleration efficiencies. They may be associated with the abundancies of the accelerated CR (as distinct from their exponents), the latter having been considered by Berezhko and Ksenofontov (1999). A possibility relates to the environment in which the particles are accelerated: near the 'accelerator' (SNR) the fraction of high  $Z$  nuclei in the ISM will be higher and it is here that the higher energy particles are accelerated (eg

Zatsepin et al., 2011). A possible scenario involves OB associations, regions where SN are in excess and the 'contaminated ISM' contains an excess of nuclei with  $Z \geq 2$ , and here the linear dimensions are great enough for the proposed mechanism.

The importance of OB associations as the site of CR acceleration was put forward by Bykov and Toptygin (2001) and Rauch et al. (2009) and, as remarked earlier, our NC may be accelerated preferentially in those in the Local Bubble, or nearby. Thus, the associations may be important for both NC and the 'background component' (characterised by  $\gamma_2$ ) with the importance for the former being greater.

## 3 Discussion of the results on the new component.

Evidence from the abundances: A clue as to the origin of the NC should come from its mass composition (and to a lesser extent from its energy spectrum) and, here, Figures 2 and 3 have relevance. It is evident that Neon and Magnesium and, to a lesser extent, Iron, are in excess in comparison with the overall abundances. These excesses should feature in the search.

The first possibility is novae, and this is considered next.

Novae as the source of the New Component?: Zatsepin and Sokolskaya (2006), in their 'three component model of cosmic ray spectra from 10 GeV to 100 PeV', attributed some of the particles below 300 GeV/nucleon to the  $3^{rd}$  component and proposed novae as candidates, as we have already remarked. In comparison with supernovae, novae have, presumably, a much reduced CR yield, but in principle this could be compensated by their much enhanced frequency.

Our own analysis of nova properties leads to a different conclusion, however.

O, B, A supergiant and Wolf-Rayet stars: These stars have very intense stellar winds (velocities of order 1000  $\text{kms}^{-1}$ ) and contribute one fifth as much kinetic energy to the Galaxy as given by SN. The energetics, at least, are reasonable. The excess Neon (Figure 2a) would favour this explanation insofar as they have excess Ne in their vicinity (eg Crowther, 2007). Concerning Wolf-Rayet stars it is interesting to note that there is one such star (Gamma Velorum) only 258 pc distant. It must be said, however, that the commonly quoted factor of 5 increase in Ne in Wolf-Rayet winds is dependent on Wolf-Rayet type and is uncertain (Crowther, 2007).

The Local Bubble: The 'Local Bubble', a rather neglected phenomenon in CR physics, seems to have resulted from perhaps 10 SN exploding in a period 1-10 My before the present and is an example of the Superbubbles which are now known to permeate galaxies in general (eg Lallement et al., 2003), although it is not as strong as some. In it the density of ionized gas is of order  $10^{-3} \text{ cm}^{-3}$ , its linear dimension is  $\approx 300$  pc and mean temperature  $\sim 10^6 \text{ K}$ . A simple calculation shows that the energy density of the gas

in the Bubble is at least of the order of that in CR, so that if equipartition of energy between CR and gas energy holds it could be relevant.

CR could have been trapped in the Bubble if the ‘walls’ are sufficiently reflective and, indeed, the ubiquitous shocks could be accelerating low energy CR even now.

The information in Figure 3 is relevant. The somewhat higher  $f_{30}$  values for the refractory elements (Mg and Fe) suggest a similar origin for the new component to CR in general, where the well-known excess for the refractories suggests that grains play an important role in the acceleration process (eg Berezhko and Ksenofontov, 1999; Meyer and Ellison, 1998, Rauch et al., 2009). It must be said, however, that Si is a disappointment although studies by Daflon and Cunha, 2004, lead to an explanation.

## 4 Conclusions.

Although there are variations in spectra from one measurement to another, the presence of ankles in the hundreds of GeV/nucleon region seems well founded; (the electron component seems to show this feature, too at least in ATIC (Panov et al., 2011)).

The explanation in terms of an extra component (the ‘New Component’) with an eventually steeply-falling energy spectrum is an attractive one.

The mass composition of this new component hints at an origin in OB associations in the Local Bubble, with a small number of SN and Wolf-Rayet stars having been active.

If substantiated (and new data from AMS should help considerably), many new studies are indicated, including aspects of the local electron spectrum, radio astronomical phenomena, gamma rays, secondary to primary ratio and isotopic compositions.

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