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DO WE SEE THE 'IRON PEAK'?

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Abstract. Recent measurements of the cosmic ray (CR) energy spectrum in the PeV region and above have confirmed the remarkable sharpness of the knee and revealed another structure at about 70 PeV, which we call the 'Iron Peak'. The position and the shape of this structure lead us to associate its likely origin with the same single source responsible for the the knee. We have analysed the shape of the single source spectrum and concluded that its mass composition is rather similar to that for the bulk of CR in the TeV $\div$ PeV region. Since it is generally accepted that these CR originate mainly in supernova explosions, this gives an additional argument in favour of our single source being a supernova remnant.

Keywords: cosmic rays, knee, single source, iron peak.

1. Introduction

The origin of cosmic rays (CR) is usually studied by analysing the general shape of the energy spectrum, mass composition and anisotropy. We would like to say that additional information can be obtained from the study of the detailed shape or the 'fine structure' of the CR energy spectrum. The 'structure' can be divided into two broad and overlapping categories: sharp discontinuities (fine structure) and slow trends. Anything other than a simple power law spectrum with an energy-independent exponent can be termed a 'structure'.

Many simulations indicate that the dominant contribution to the observed CR is from nearby sources, where the non-uniformity of their space distribution plays a significant role. If the production of CR by these sources has an explosive character as from supernovae (SN) and subsequent remnants (SNR), then their random explosions make the non-uniformity of the CR space-time distribution even stronger. This has to result in the appearance of a fine structure in the CR spectrum at some level.

2. Evidence for a fine structure in the knee region

The most prominent structure in the CR spectrum is the knee, at about $3 \div 4$ PeV. Although it was discovered more than half a century ago, its origin is still debated. More than a decade ago we put forward a model in which the remarkable sharpness of the knee can be understood if a 'single source' is largely responsible [8, 9]. The CR component that makes the dominant contribution at the knee was assumed to be helium (He) nuclei [12]. An additional argument in favour of the single source model of the knee was the observation of a small bump in the $10 \div 20$ PeV energy interval, attributed to the CNO group of nuclei. The sharpness of the knee is caused by the following: the source is in fact single, the spectrum of He nuclei is peak-like and has a sharp cut-off above the maximum acceleration rigidity of $\sim 1.5 \div 2$ PV, and the amount of Li, Be, B nuclei between the He and CNO peaks is negligible.

In our paper [12], we assumed the possible existence of a further structure, a peak at an energy of above 50 PeV associated with the iron (Fe) group of nuclei, but at that time we could not claim to have observed it. However, very recently several experiments which have good energy resolution and statistical accuracy have revealed irregular behavior of the spectrum in the $10 \div 100$ PeV energy range, with the possible existence of the bump above 50 PeV. These experiments are GAMMA [15, 20], TUNKA-25,133 [4, 19], IceTop [24], KASCADE-Grande [6] and Yakutsk [18].

3. Origin of the fine structure

In the following, we construct a model of the primary CR spectrum (I_{CR}) in the knee region and above as composed of a smooth background (I_{BGRD}) and a contribution from the single source (I_{SS}). The background is produced by a multitude of various sources and has the shape of two power laws [23] far below the knee and above the knee. In the knee region these two power laws are connected with each other by a smooth transition line with sharpness of 0.3 inherent for the Galactic Diffusion Model (GDM) [9]. In order to find the average contribution of the single source to the background, we have determined this contribution for 10 individual energy spectra, and have averaged them. The results are shown in Figs. 1 and 2.

The excess over the background at $\log(E/E_{\mathrm{k}}) = 1.1 \div 1.3$ is clearly seen in Fig. 2b. If the knee position is at $E_{\mathrm{k}} \approx 4$ PeV and is caused by a dominant contribution of He nuclei, then the observed excess

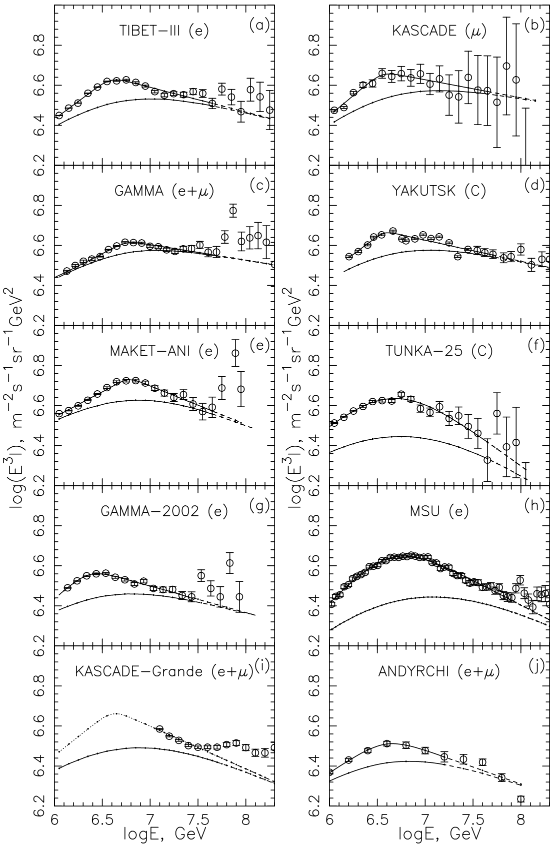

Figure 1. Energy spectra of primary CR, measured by the following EAS arrays: Tibet-III (a) [2], KASCADE (b) [3], GAMMA (c) [15], Yakutsk (d) [17], Maket-ANI (e) [7], Tunka-25 (f) [19], GAMMA-2002 (g) [14], MSU (h) [25], KASCADE-Grande (i) [6] and Andyrchi (j) [22]. The symbols 'e', 'μ' and 'C' in brackets indicate the measured EAS components: electromagnetic, muon or Cherenkov light, respectively. The upper full lines are fits of these spectra by the Ter-Antonyan and Haroyan formula [23]. The lower full lines are the spectra expected if the best fit sharpness obtained in the above fit is replaced by 0.3 – the value expected in the Galactic Diffusion Model. The dashed lines are extrapolations of these fits to energies above the fitted range.

corresponds to energies of $50 \div 80$ PeV and the contribution of the Fe-group nuclei, if their cut-off energies are proportional to the nuclear charge Z.

Since we adopted the approximation that $I_{\mathrm{CR}} = I_{\mathrm{BGRD}} + I_{\mathrm{SS}}$, the excess Δ shown in Fig. 2b is equal to $\Delta = \log(I_{\mathrm{CR}}/I_{\mathrm{BGRD}}) = \log(1 + I_{\mathrm{SS}}/I_{\mathrm{BGRD}})$, and then

$$I_{\mathrm{SS}} = I_{\mathrm{BGRD}}(10^{\Delta} - 1). \qquad (1)$$

The mean background was taken of the same form [23] used in the analysis of the 10 individual spectra. This background has a differential exponent of 2.7 at low energies, $\log E < 5$, and 3.1 at high energies, $\log E > 8$. The sharpness of the knee is $S = 0.3$ at $\log E_{\mathrm{k}} = 6.5$. The absolute intensity has been taken at $\log E = 5$ from [26]. The energy spectrum of the single source

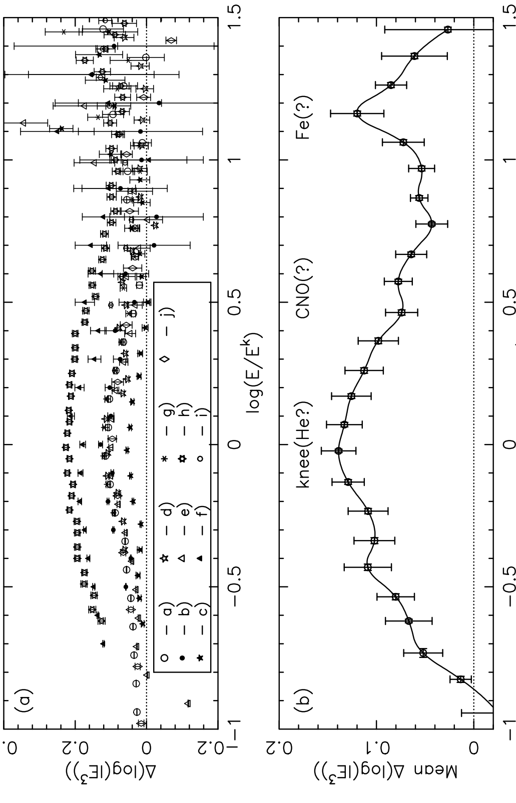

Figure 2. Fine structure of the primary cosmic ray energy spectrum, shown as the difference between the measured intensities and the 'background' (see the text): (a) the individual excesses. The key to the symbols associated with arrays is given in the box below the dotted zero line. Arrays are denoted by the same signs as in the panels in Fig. 1. (b) the unweighted mean profile of the excess above the GDM with the likely charge assignments. The knee is at $\log(E/E_{\mathrm{k}}) = 0$.

was derived from this background and the excess Δ (Fig. 2b), using Eq. 1, and it is shown by open squares in Fig. 3.

The relative mass composition has been derived by fitting 5 individual components: P, He, CNO (carbon, nitrogen and oxygen), M (neon, magnesium, silicon and sulphur) and Fe (argon, calcium and iron) to this single source spectrum. The shape of the energy spectrum for each mass group was taken as typical for the Monogem-like SNR. The maximum rigidity of nuclei accelerated in the single source is taken to be the same for all the nuclei, so that the maximum energy is proportional to the charge, Z.

Since the energy spectra of all 5 mass groups in CR from the single source have essentially a non-power law shape 'on arrival', it is unreasonable to describe the mass composition in terms of the relative fractions of their flux at a fixed energy per particle (or per nucleon). These fractions would have a strong variation with energy. Instead we derive the abundances as relative

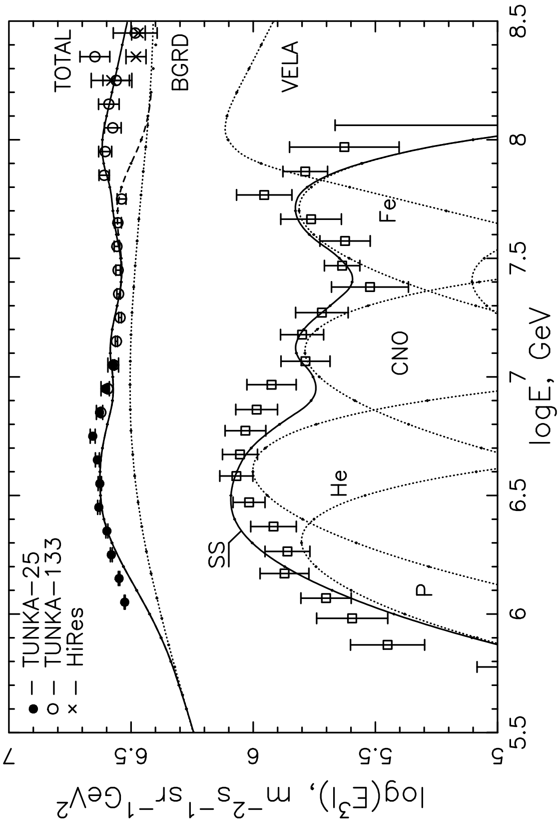

Figure 3. The energy spectrum of CR from the single source and its interpretation. The full line denoted as BGRD is the background spectrum used to convert the excess in Fig. 2b to the single source spectrum (represented by open squares). The dotted lines are best fit contributions from 5 CR mass groups: P, He, CNO, M and Fe. The full line denoted as SS is the sum of these 5 components. Full and open circles are from TUNKA [4, 19], asterisks – from HiRes [1]. Dashed line above 50 PeV in the upper plot – the spectrum expected for just background and single source contributions, without the Vela pulsar. The possible contribution of the Vela pulsar was calculated assuming that it is an isolated pulsar [11] with 1 % of its rotation energy loss converted to the emission of just Fe nuclei.

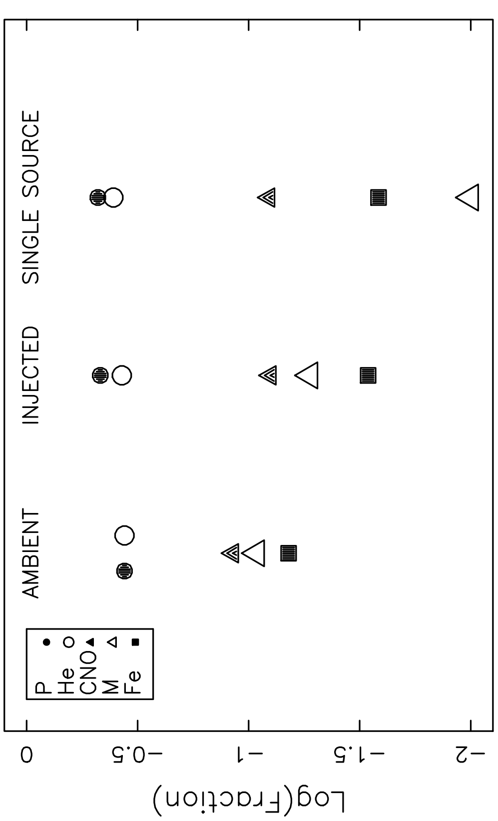

Figure 4. The 'AMBIENT' CR mass composition taken from Panov et al. [21] at $\log E = 3$ compared with the 'INJECTED' CR mass composition recalculated from 'AMBIENT', using the 'Leaky Box Model', and our 'SINGLE SOURCE' composition. The similarity of the INJECTED and SINGLE SOURCE compositions (apart from the M-component) is remarkable.

fractions of the energy content contained in each mass group with respect to the total energy carried by CR from the single source. The abundances obtained for the 5 mass groups in the CR from the single source are: P – 0.477, He – 0.406, CNO – 0.081, M – 0.010, Fe – 0.026, with accuracy typically 15 % for He and CNO and 30 % for P, M and Fe. For the ambient primary CR with their steep power law energy spectra for all 5 mass groups, the mass composition at lower energies coincides with that of the background spectrum since $I_{\mathrm{SS}} \ll I_{\mathrm{BGRD}}$ and there is no difference between the two definitions since both give the same values for the abundances.

If all CR sources in the Galaxy are the same, then the average injection abundances (at a fixed energy per nucleus) can be derived by dividing the observed CR abundances by the mean lifetime against escape from the Galaxy. Direct measurements of cosmic ray energy spectra have only been made up to about 10^5 GeV/nucleus. As a datum we use the directly measured intensities (fractions) from ATIC measurements [21] at a lower 10^3 GeV/nucleus energy, where they have good accuracy.

The necessary mean lifetimes for escape are taken from the 'Leaky Box Model' of particle diffusion, in which the mean lifetime is proportional to Z. The energy dependence of the lifetime $\tau(E)$ is taken as $\tau(E) = T_0 E^{-\delta} + \tau_0$, where $\delta = 0.5$ for the anomalous diffusion modeli [10], $T_0 = 4\times10^7$ year, $\tau_0 = 1.1\times10^4$ y, E in GeV.

The ambient mass composition from Panov et al. [21] at $\log E = 3$, and the 'effective' injected mass composition recalculated from it, are shown in Fig. 4 together with our single source composition.

It is remarkable to observe the general similarity of our single source injection and the 'injected' mass compositions in basic nuclei. If indeed the bulk of the observed cosmic rays originate from SNR, the similarity of the general ‘injected’ mass compositions and our injected ‘single source’ mass compositions gives an additional argument that our single source is also an SN and its subsequent SNR.

4. Discussion

Haungs [16] interpreted the observed spectral flattening above 20 PeV as due to the transition from the CNO-group to the M-group of sub-iron nuclei (Ne, Mg, Si and S) and the steepening above 100 PeV as due to the end of Galactic CR and the gradual transition to Extragalactic CR. Measurements of the shower age parameter by GAMMA [20] and the EAS maximum depth by the TUNKA-133 [5] experiments, as well as the spectrum of muon-rich showers by KASCADE-Grande [13] show that the CR mass composition above 20 PeV becomes progressively heavier, approaching that in which Fe nuclei dominate. Looking at Fig. 3 we agree that such a structure at 20 PeV exists. We can also say that the observed behaviour of the mass composition can be seen in our single source model.

As for the steepening beyond 100 PeV, measurements of the energy spectrum by GAMMA and TUNKA-133 give support to the existence of this structure, although with less statistical accuracy. They also hint that steepening could occur at about 200 PeV (Fig. 3). An additional argument in favour of the end of dominant Fe is the trend to a lighter mass composition above $100 \div 200$ PeV. We think that the interpretation of the gradual steepening above 100 PeV in terms of the end of Galactic CR is principally the same as in the Galactic Diffusion Model, which ignores the evident sharpness of the knee. We prefer the scenario in which the steepening of the spectrum in this energy region means the end of the contribution of the single source and the origin of CR above 100 PeV is still Galactic, but from a background of other more powerful sources.

5. Conclusion

We have examined the fine structure of the CR energy spectrum in the knee region and above, and have demonstrated how the analysis of this structure can help in studying the origin of CR in this energy region. We have shown that the new data give strong support to the conclusion that this fine structure is caused by the contribution of a single nearby and recent source, most likely an SNR. The steepening of the CR energy spectrum beyond the ‘Iron Peak’ most likely indicates the end of the contribution of the single source.

Acknowledgements

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Discussion

Bozena Czerny — From the energetics point of view, is a single supernova enough to supply the required number of particles?

Anatoly Erlykin — The brief answer is ‘YES’, if the standard supernova with explosion energy $\sim 10^{51}$ erg converted $\sim 10\,\%$ of it into cosmic rays. A more detailed answer: the number of particles from the standard supernova depends on distance and age. Our estimates of the needed distance and age are: ~ 300 pc and $\sim 10^5$ years.