Astrophys. Space Sci. Trans., 7, 145–150, 2011
www.astrophys-space-sci-trans.net/7/145/2011/
doi:10.5194/astra-7-145-2011

Astrophysics and Space Sciences Transactions

Do we see an ‘Iron Peak’ ?

A. D. Erlykin[1] **and A. W. Wolfendale**[2]

[1]P. N. Lebedev Physical Institute, Moscow, Russia
[2]Durham University, Durham, UK

Received: 1 October 2010 – Revised: 27 November 2010 – Accepted: 3 January 2011 – Published: 21 April 2011

Abstract. An update of the fine structure in the cosmic ray (CR) energy spectrum at PeV and tens of PeV energies is presented. The existence of the bump at 50–80 PeV found in the GAMMA experiment is supported by 9 other experiments. If it is a real feature it might indicate the existence of the so called ‘Iron Peak’, i.e. the end of the contribution of a ‘Single Source’ to the background of CR from other sources. We argue that the new feature in the fine structure of the CR energy spectrum makes the evidence in favour of the presence of a ‘Single Source’ stronger than before.

1 Introduction

In 1997 we put forward the idea that the remarkable sharpness of the knee at 3–4 PeV in the cosmic ray (CR) energy spectrum is due to the dominant contribution of a single source. This sharpness could be the consequence of a sharp cutoff of the maximum accelerated energy in the source. Another argument in favour of the single source model was the fine structure of the spectrum in the vicinity of the knee i.e. not just a single smooth transition, but a sharp one. Specifically, we found evidence for two ‘knees’ (Erlykin and Wolfendale, 1997). Later we updated the analysis using the 40 size spectra of extensive air showers (EAS) available at that time. We confirmed the conclusion that the observed sharpness of the knee is higher than expected in the Galactic Diffusion Model (GDM) (Ginzburg and Syrovatskii, 1964). We extended the analysis on the spectra of Cherenkov light from EAS and found the same fine structure as observed with the detectors of EAS charged particles (Erlykin and Wolfendale, 2001). Later on, we came to the conclusion that the most likely nucleus, dominant in the knee, was helium. In this case the second observed structure in the energy spectrum at 12–16 PeV is due mainly to oxygen (Erlykin and Wolfendale, 2006a). If this is true, at even higher energies, about 40–50 PeV, one can expect another structure due to iron.

The aim of this paper is to review the present situation around the knee and update the status of the single source model.

2 New data

Since the beginning of this decade several new measurements of the CR energy spectrum have been published (Amenomori et al., 2008; Apel et al., 2009; Garyaka et al., 2008; Ivanov et al., 2009; Chilingarian et al., 2007; Korosteleva et al., 2007; Garyaka et al., 2002; Vishnevskaya et al., 2002; Haungs, 2009; Petkov, 2009). They are shown in Fig. 1. We do not include here the EAS-TOP+MACRO measurements (Aglietta et al., 2004) since their authors showed the spectra of light and heavy elements separately. We omitted also the results of Ice-Top (Stanev, 2010) since they are still preliminary.

2.1 Sharpness

The sharpness of the spectral change can be defined in different ways. We used two definitions. In the first one the position of the knee ($log E_1^k$) has been determined as the point with the maximum sharpness of the spectrum, the sharpness S_1 being defined as (Erlykin and Wolfendale, 1997)

$$S_1 = -\frac{d^2(log I)}{d(log E)^2} \quad (1)$$

The results are shown in columns 2 and 3 of Table 1.

The second definition assumes that spectra both before and after the knee can be fitted by power laws. We fitted 10 spectra in Fig. 1 by the expression

$$I(E) = AE^{-\gamma}(1+(\frac{E}{E^k})^{\delta})^{-\frac{\Delta\gamma}{\delta}} \quad (2)$$

Correspondence to: A. D. Erlykin
(erlykin@sci.lebedev.ru)

Published by Copernicus Publications on behalf of the Arbeitsgemeinschaft Extraterrestrische Forschung e.V.

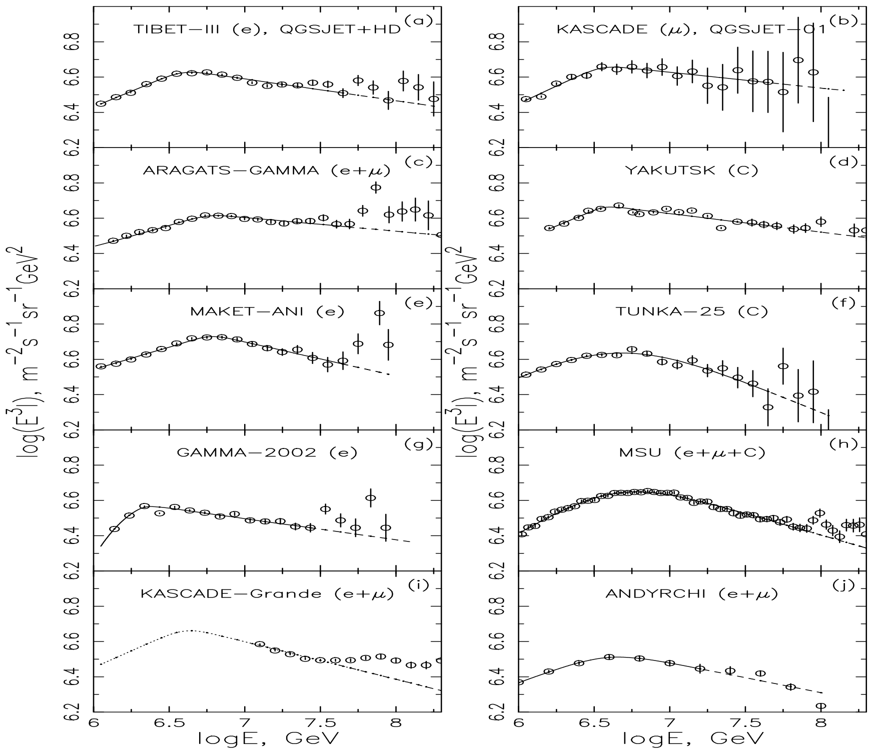

Fig. 1. Energy spectra of primary CR, measured by the Tibet-III **(a)**, KASCADE **(b)**, GAMMA **(c)**, Yakutsk **(d)**, Maket-Ani **(e)**, Tunka-25 **(f)**, GAMMA-2002 **(g)**, MSU **(h)**, KASCADE-Grande **(i)** and Andyrchi **(j)** arrays. Symbols e, μ and C in brackets indicate the measured EAS component: electromagnetic, muon or Cherenkov light respectively. Notations QGSJET+HD (heavy dominant) in (a) and QGSJET-01 in (b) indicate the interaction model used for the transition from the measured parameters to the primary energy. Full lines are fits by the expression (2) with best fit parameters shown in the last five columns of Table 1. Dashed lines are extrapolations of these fits to the energy above the fitted range.

Table 1. Data for Fig. 1. Columns 2 and 3 show parameters determined by expression (1), columns 4-8 - by expressions (2) and (3)

Array	$logE_1^k$	S_1	$logE_2^k$	γ	$\Delta\gamma$	δ	S_2
Tibet-III	6.60	1.34±0.21	6.59	2.64	0.48	8.85	2.44±0.77
KASCADE	6.60	3.07±0.77	6.55	2.60	0.49	8.43	2.34±4.86
GAMMA	6.61	1.19±0.30	6.76	2.76	0.32	10.0	1.84±0.43
Yakutsk	6.69	3.56±0.65	6.57	2.64	0.46	15.7	4.17±4.31
Maket-ANI	6.70	1.53±0.53	6.78	2.75	0.44	12.9	3.30±3.30
Tunka	6.50	1.44±0.60	6.64	2.59	0.75	1.64	0.71±0.13
GAMMA-2002	6.39	4.16±0.22	6.30	2.12	0.99	10.0	5.73±0.33
MSU	6.79	1.12±0.42	6.64	2.50	0.75	2.27	0.98±0.37
KASCADE-Grande	6.60	3.07±0.77	6.61	2.62	0.59	7.88	2.69±1.15
Andyrchi	6.61	0.76±0.33	6.58	2.68	0.48	3.54	0.98±0.53

Here γ is the power law index of the spectrum before the knee, which changes by $\Delta\gamma$ above the knee. Between these regions there is a transition range which is described by the sharpness parameter δ. The sharpness S_2 in this approach is connected with δ as

$$S_2 = \delta \Delta\gamma \frac{ln10}{4} \tag{3}$$

We have found best fit values for these parameters using the least squares method with the MINUIT code (James and Roos, 1998). They are shown in the 5 last columns of Table 1. The energy range, in which we fitted spectra (on average up to 50 PeV) and the fit itself, are shown by the full line in Fig. 1. The linear extrapolation of the fit to higher energies in double logarithmic coordinates is indicated by the dashed line.

The results is that the knee in the primary energy spectrum is indeed rather sharp. Both values of the sharpness correlate with each other (the weighted correlation coefficient is 0.93) and are substantially higher than 0.3, which is the characteristic value for the GDM.

2.2 Fine structure

We define the ‘fine structure’ of the spectrum as the existence of reliable deviations from the power law fits described in the previous section. Deviations of the actual intensities from these fits and their extrapolations for all 10 spectra are shown in Fig. 2a. In order to remove the difference between the energy scales of all spectra and reveal the peculiarities in their shape we refer the deviations from the fit (2) in the individual spectra to the individual energy of the knee $logE_2^k$. Mean values of the deviation are shown in Fig. 2b.

The irregularity at the position of the knee, $log(E/E^k) = 0$ is not seen since expression (2) gives a good fit to the spectrum in the knee region. The small irregularity at $log(E/E^k) = 0.5 - 0.7$ found in (Erlykin and Wolfendale, 1997, 2001) is confirmed in the new spectra (the structure was somewhat bigger earlier). The progress in these new measurements lets us proceed to higher energies. Here, a new feature can be seen at $log(E/E^k) = 1 - 1.3$. It was first noticed in (Garyaka et al., 2008) and now confirmed by most of the other spectra (those of KASCADE, Yakutsk and Andyrchi, although they do not show the clear excess, do not contradict its existence). The different choice of binning changes slightly the shape of the excess but in no case eliminates it, because the vast majority of the points beyond $log(E/E^k) \approx 1$ lie above the extrapolations.

If indeed light nuclei: He and, partly, H, dominate in the knee then the next irregularity at $log(E/E^k) = 0.5 - 0.7$ can be due to the CNO-group of nuclei and the second one at $log(E/E^k) = 1 - 1.3$ - to the Fe-group. Minima at $log(E/E^k) = 0.15$ and 0.8 can be associated with the lack of Li, Be, B and sub-iron elements in the primary CR at PeV energies. The peaks marked 'CNO(?)' and 'Fe(?)' are at the correct places for the nuclei which are thought to form the bulk of the CR after hydrogen and helium. The decrease of the intensity after the Fe peak at $log(E/E^k) = 1.4 - 1.5$ can be associated with the end of the contribution of the single source to the background of CR produced by other sources.

2.3 Other evidence

Recently, the PAMELA and ATIC collaborations have claimed an excess of positrons (Adriani et al., 2009) and electrons ($e^- + e^+$) (Chang et al., 2008) in the primary CR. The evidence is in the form of a sudden upturn in the positron fraction at $\sim 3 - 5$ GeV, leading to a bump in the $e^- + e^+$ spectrum at ~ 500 GeV. The peak is some 3-4 times the 'background level' formed by a smooth steepening of the spectrum from energies below the bump. The other measurements although showing somewhat smaller intensity in the bump confirmed an irregular behavior of the spectrum in this region (Abdo et al., 2009) and its sharp steepening at TeV energies above the bump (Aharonian et al., 2008, 2009), which creates a feature similar or even sharper than the knee at PeV energies. These publications caused great interest and inspired many attempts at their explanation (see references in Barger et al., 2009). The bulk of the proposed models suggested mechanisms in which the additional electrons and positrons were created by the interaction, annihilation or decay of dark matter particles. Other models proposed astrophysical scenarios with extra electrons and positrons created, accelerated and emitted by various astrophysical sources. We consider these latter scenarios as more likely, not only because dark matter particles are still elusive, but such models face the difficulty of an absence of extra antiprotons in the PAMELA data (Adriani et al., 2010), which should inevitably be produced in processes including dark matter particles.

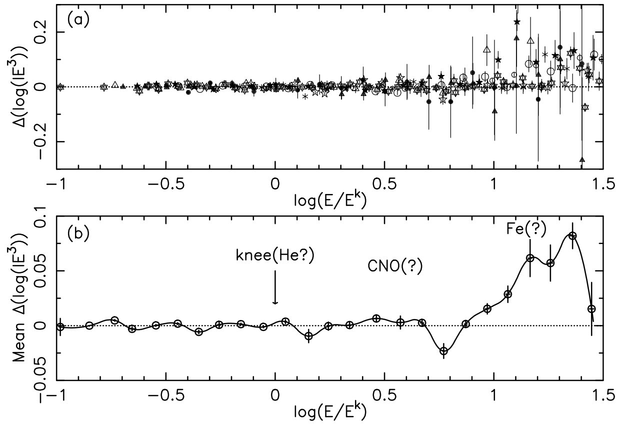

Fig. 2. Fine structure of the PCR energy spectrum. The irregularity at the position of the knee, $log(E/E^k) = 0$, is not seen since the expression (2) gives a good fit of the spectrum in the knee region.

3 Discussion of the knee and the 'electron bump'

We discuss astrophysical models here because they seem to us more realistic and according to our view they give support to our single source model. Here we present arguments in favor of such a view.

(i) The essence of the single source model is that CR sources are non-uniformly distributed in space and time. As a consequence the CR energy spectrum observed at the Earth can carry traces of this non-uniformity, i.e. irregularities of some kind or a 'fine structure'. In particular the substantial contribution of just the nearby and recent single source (SNR or pulsar) can be the cause of the knee at PeV energies.

(ii) The observed sharpness of the knee is due to several reasons: (a) the source is relatively close to the solar system and the energy spectrum of its CR is not distorted by propagation effects. Its shape is close to that of the production spectrum. Below the knee it is rather flat ($\gamma \approx 2.1$) compared with the bulk of CR ($\gamma \approx 2.7$) and its contribution is more pronounced at high energies. (b) The CR energy spectrum has a sharp cutoff at the maximum acceleration energy. (c) If the He component is dominant at the knee it gives an additional sharpness since we must expect a gap between the He and CNO group of nuclei. (d) Since the source is mainly 'single' the smoothing effect on the knee sharpness due to the spread of characteristics inevitable in the case of multiple sources is at a minimum.

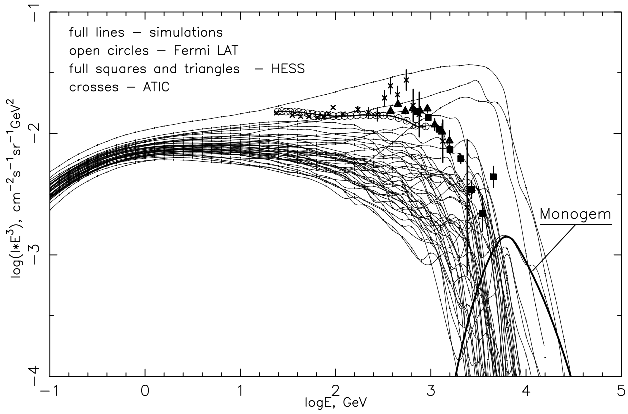

Fig. 3. Examples of predicted electron spectra for different time-space distributions of SNR (Erlykin and Wolfendale, 2002). Experimental data: crosses - ATIC (Chang et al., 2008), open circles - Fermi LAT (Abdo et al., 2009), full squares and triangles - HESS (Aharonian et al., 2008, 2009). The bumps in the simulated samples are generally at an energy higher than the observed electron-positron bump, which is at ∼500 GeV. This is interpreted by us as indicating that these electrons+positrons are secondaries to 'our' SNR-accelerated protons and nuclei. The thick solid line in the TeV region shows the contribution to electrons expected from the Monogem Ring SNR (Erlykin and Wolfendale, 2002)

.

(iii) The electron component of CR is even more sensitive to the presence of nearby and recent sources than protons and nuclei, since electrons from remote and old sources suffer not only from diffusive losses, but also from rising energy losses. Indeed, in our paper devoted to SNR and the electron component (Erlykin and Wolfendale, 2002) we showed how different the electron spectra could be for different samples of the time-space distribution of SNR in our Galaxy. We show this collection of electron spectra in Fig. 3. The simulations were made assuming that the electrons are accelerated in the SNR in a similar manner to that for protons. The fine structure of the spectrum appears already at energies above 100 Gev and is clearly seen as bumps in the TeV region caused by the recent and nearby SNR. Such fine structure is confirmed by ATIC observations (Panov et al., 2011). Comparison of our simulations with the experimental data was presented in (Erlykin and Wolfendale, 2009).
(iv) In the absence of likely sources of positrons within the SNR, the observations dictate that the positrons come from another process. SNR and pulsars are usually immersed in the envelopes of gas and radiation fields: remnants of the SN explosion (SNR), and pulsar wind nebula (PWN). The accelerated particles interact with this environment and create electron-positron pairs. These secondary positrons and electrons will have energies less than those directly accelerated and their ensuing bump will be at a lower energy: tens of GeV is not unreasonable.
(v) The energy spectrum of electrons from nearby and recent sources would be as flat as the production spectrum of the accelerated particles and create a feature similar to the knee in the spectrum of primary CR nuclei. The sharpness of the 'electron knee' in this scenario is supported by HESS measurements (Aharonian et al., 2008, 2009) and is due to the sharpness of the knee for primary nucleons, rising energy losses of electrons and positrons at TeV energies and a small pile up of electrons which initially had an energy higher than the knee, but lost it during propagation. The calculations made in some works support such a possibility (Barger et al., 2009; Erlykin and Wolfendale, 2002; Hu et al., 2009; Wang et al., 2010; Shaviv et al., 2009; Malyshev et al., 2009; Blasi, 2009; Fujita et al., 2009; Piran et al., 2009). There are, however, attempts to give a methodical explanation of the PAMELA and ATIC excess by contamination (Schubnell, 2009).
(vi) The magnitude of the bump from the single source with respect to the background in electrons can be greater than that in nuclei and this can be understood. In view of the rapidly increasing energy losses for electrons in the general interstellar medium, compared with only a diffusive loss for nuclei, the electron background is relatively lower. We estimate that the bump (ATIC) contains an energy of $\sim 10^{-5}$ eVcm^{-3}; for reference, our single source contributes about $2 \cdot 10^{-4}$ eVcm^{-3} to the CR spectrum.
(vii) Possible candidates for the 'single source' are the Monogem Ring SNR with an associated pulsar B0656+14 (Thorsett et al., 2003; Erlykin and Wolfendale, 2004) and the Vela X SNR with an associated pulsar J0833-45 (Bhadra, 2006). The latter is as young as 11 kyear and can contribute to CR at Earth only if Vela X's magnetic fields are not strong enough to trap accelerated PeV particles. If there is no such confinement the pulsar J0833-45 with its maximum rigidity of 2.5 PV can be a good candidate for the contribution to the 'Iron Peak' at an energy of 65 PeV.

Due to the hard energy spectrum our candidates for the single source can have an effect on the anisotropy only at PeV energies (Erlykin and Wolfendale, 2006b). However, their effect is destructive, i.e. it reduces the amplitude of the anisotropy since both sources are in the third quadrant of the Outer Galaxy, i.e. in the opposite direction to the bulk of SNR which are concentrated in the Inner Galaxy.

4 Conclusions

We have analysed the ten new energy spectra which have appeared in papers published since the last update of our single source model (Erlykin and Wolfendale, 2001). All the previous findings (sharpness and the fine structure of the knee) are confirmed by the new data. The advance to a higher energy of about 10^8 GeV lead us to confirm the likely existence of a new feature - another irregularity in the spectrum at an energy of 65±15 PeV, claimed first in (Garyaka et al., 2008). If the dominant contribution to the knee is due to primary

He-nuclei, this new irregularity is just where primary iron nuclei should appear and create the so called ‘Iron Peak’.

We consider that the latest findings of the irregularities in the electron and positron spectra (’electron bump or knee’) can have the same origin as the ‘hadron knee’ in the spectra of the primary nuclei, i.e. they are due to the non-uniformity of the time-space distribution of CR sources, and if true, it is additional support for the single source model. Some quantitative calculations give support to such a scenario (Hu et al., 2009)

It is interesting to postulate that the last HESS point at ~ 4500 GeV (a high value) could represent part of a signature of SNR-accelerated electrons from a source such as the Monogem Ring (see Fig. 3); certainly it is in the energy region where we expect a bump. Confirmation of this structure by future measurements of the electron spectrum at energies above several TeV could be one of the tests for the ‘single source’ model. More astronomical studies would also help.

Finally studies are continuing of the likely ‘nearby’ few sources to the single source peak, and the physics associated with the undoubted concave nature of the primary nuclear spectra at energies well below the knee.

Acknowledgements. The authors are thankful to the Ralph Kohn Foundation for their interest and financial support of this work.

Edited by: K. Scherer
Reviewed by: two anonymous referees

References

Abdo, A. A., Ackermann, M., Ajello, M. et al.: Measurement of the cosmic ray e++e- spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope, Phys. Rev. Lett., 102, 181101, 2009.

Adriani, O., Barbarino, G. C., Bazilevskaya, G. A. et al.: An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV, Nature, 458, 607–609, 2009.

Adriani, O., Barbarino, G. C., Bazilevskaya, G. A. et al.: PAMELA results on the cosmic ray antiproton flux from 60 MeV to 180 GeV in kinetic energy, Phys. Rev. Lett., 106, 121101, 2010.

Aglietta, M., Alessandro, B., Antonioli, P. et al.: The cosmic ray primary composition between 1015-1016 eV from extensive air showers electromagnetic and TeV muon data, Astropart. Phys., 20, 651–652, 2004.

Aharonian, F., Akhperjanian, A. G., Barres de Almeida, U. et al.: Energy spectrum of cosmic-ray electrons at TeV energies, Phys. Rev. Lett., 101, 261104, 2008.

Aharonian, F., Akhperjanian, A. G., Anton, G. et al.: Probing the ATIC peak in the cosmic-ray electron spectrum with HESS, Astron. Astrophys., 508, 561–564, 2009.

Amenomori, M., Ayabe, S., Bi, X.-J. et al.: The cosmic-ray Energy spectrum around the knee measured by the Tibet-III air-shower array, Nucl. Phys. B, 175–176, 318–321, 2008.

Apel, W. D., Arreaga, J. C., Badea, A. F. et al.: Energy spectra of elemental groups of cosmic rays: update of the KASCADE unfolding analysis, Astropart. Phys., 31, 86–91, 2009.

Barger, V., Gao, Y., Keung, W.-Y. et al.: Dark matter and pulsar signals for Fermi LAT, PAMELA, ATIC, HESS and WMAP data, Phys. Lett. B, 678, 283–292, 2009.

Bhadra, A.: Contribution of a nearby pulsar to cosmic rays observed at Earth, Astropart. Phys., 25, 226–232, 2006.

Blasi, P.: Origin of the positron excess in cosmic rays, Phys. Rev. Lett., 103, 051104, 2009.

Chang, J., Adams, J. H., Ahn, H. S. et al.: An excess of cosmic ray electrons at energies of 300–800 GeV, Nature, 456, 362–365, 2008.

Chilingarian, A., Gharagyozyan, G., Ghazaryan, S. et al.: Study of extensive air showers and primary energy spectra by MAKET-ANI detector on Mountain Aragats, Astropart. Phys., 28, 58–71, 2007.

Erlykin, A. D. and Wolfendale, A. W.: A single source of cosmic rays in the range 1015–1016 eV, J. Phys. G: Nucl. Part. Phys., 23, 979–989, 1997.

Erlykin, A. D. and Wolfendale, A. W.: Structure in the cosmic ray spectrum: an update J. Phys. G: Nucl. Part. Phys., 27, 1005-1030 (2001)

Erlykin, A. D. and Wolfendale, A. W.: Supernova remnants and the origin of the cosmic radiation: the electron component, J. Phys. G: Nucl. Part. Phys., 28, 359–378, 2002.

Erlykin, A. D. and Wolfendale, A. W.: Cosmic rays and the Monogem supernova remnant, Astropart. Phys., 22, 47–63, 2004.

Erlykin, A. D. and Wolfendale, A. W.: The nature of the knee in the cosmic ray energy spectrum, J. Phys. G: Nucl. Part. Phys., 32, 1–7, 2006a.

Erlykin, A. D. and Wolfendale, A. W.: The anisotropy of galactic cosmic rays as a product of stochastic supernova explosions, Astropart. Phys., 25, 183–194, 2006b.

Erlykin, A. D. and Wolfendale, A. W.: The knee in the cosmic ray energy spectrum, Proc. 31st Int. Cosmic Ray Conf., Lodz, Poland, July 7–15, ID:0301, 2009.

Fujita, Y., Kohri, K., Yamazaki, R. et al.: Is the PAMELA anomaly caused by supernova explosions near the Earth ? Phys. Rev. D, 80, 063003, 2009.

Garyaka, A. P., Martirosov, R. M., Procureur, J. et al.: The cosmic ray energy spectrum around the knee, measured with the GAMMA array at Mt. Aragats, J. Phys. G: Nucl. Part. Phys., 28, L23–L32, 2002.

Garyaka, A. P., Martirosov R. M., Ter-Antonyan, S. V. et al.: An all-particle primary energy spectrum in the 3-200 PeV energy range, J. Phys. G: Nucl. Part. Phys., 35, 111201, 2008.

Ginzburg, V. L. and Syrovatskii, S. I.: The origin of cosmic rays, Pergamon Press, 1964.

Haungs A.: The cosmic ray energy spectrum measured with KASCADE-Grande, 31st Int. Cosmic Ray Conf., Lodz, Poland, July 7–15, 175–182, 2009.

Hu, H.-B., Qiang, Y., Wang Bo et al.: On the e+e- excesses and the knee of the cosmic ray spectra hints of cosmic ray acceleration in young supernova remnants, Astrophys. J., 700, L170–173, 2009.

Ivanov, A. A., Knurenko, S. P. and Sleptsov, I. E.: Measuring extensive air showers with Cherenkov light detectors of the Yakutsk array: the energy spectrum of cosmic rays, New J. Phys., 11, 065008, 2009.

James, F. and Roos, M.: CERN Program Library, http://wwwasdoc.web.cern.ch, 1998.

Korosteleva, E. A., Prosin, V. V., Kuzmichev, L. A. et al.: Measurement of cosmic ray primary energy with the atmospheric Cherenkov light technique in extensive air showers, Nucl. Phys. B, 165, 74–80, 2007.

Malyshev, D., Cholis, I. and Gelfand, J.: Pulsars versus dark matter interpretation of ATIC/PAMELA, Phys. Rev. D, 80, 063005, 2009.

Panov, A. D., Zatsepin, V. I., Sokolskaya N. V. et al.: Fine structure in the cosmic ray electron spectrum measured by ATIC, Izvestia RAN, ser. fiz., 75, 350–353, 2011.

Petkov, V. B.: The Andyrchi-BUST experiment: primary spectrum and composition around the knee, 31st Int. Cosmic Ray Conf., Lodz, Poland, July 7–15, 127–132, 2009.

Piran, T., Shaviv, N. J. and Nakar, E.: SNRs as a simple explanation for PAMELA/ATIC anomalies, 44th Rencontres de Moriond 'Very High Energy Phenomena in the Universe', La Thuile, Italy, http://moriond.in2p3.fr/J09/transparents/piran2.pdf, 2009.

Schubnell, M.: Measurement of cosmic-ray positrons and electrons, an experimentalist's point of view, 44th Rencontres de Moriond 'Very High Energy Phenomena in the Universe', La Thuile, Italy, http://moriond.in2p3.fr/J09/transparents/schubnell.ppt, 2009.

Shaviv, N. J., Nakar, E. and Piran, T.: Inhomogenity in cosmic ray sources as the origin of the electron spectrum and the PAMELA anomaly, Phys. Rev. Lett., 103, 111302, 2009.

Stanev, T.: The Ice-Top experiment in 2010, Vulcano 2010 Workshop: Frontier Objects in Astrophysics and Particle Physics, Vulcano, Italy, May 23–29, http://www.lnf.infn.it/conference/vulc2010/slides/Vulcan10/Saturday_29_files/stanev_icetop10.pd, 2010.

Thorsett, S. E., Benjamin, R. A., Brisken, W. F. et al.: Pulsar PSR B0656+14, the Monogem Ring and the origin of the knee in the primary cosmic-ray spectrum, Astrophys. J., 592, L71–L73, 2003.

Vishnevskaya, E. A., Kalmykov, N. N., Kalmykov, V. N. et al.: Energy spectrum of cosmic rays in the knee region and studies of different components of extensive air showers, Bull. Russian Academy of Sciences, 66, 1723–1726, 2002.

Wang, Bo, Yuan, Q., Fan, Ch. et al.: A sudy on the sharp knee and fine structures of cosmic ray spectra, Science China, Physics, Mech. Astron., 53, 842–847, 2010.