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Energy spectra of light species of primary cosmic rays in the energy range from 10 TeV to 100 PeV

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Abstract

A new paradigm of multisensory observations joined multiband measurements of the radiation coming from celestial objects to develop and confirm models of the origin of high-energy cosmic rays (CR). The integral parameters of the cosmic ray flux, such as energy spectra and mass composition, mostly measured in the last century, deliver useful information on the CR origination. Especially useful was an approach to disentangle the overall cosmic ray flux and obtain separate energy spectra of different mass groups. The MAKET-ANI surface array operated on Aragats Mt. in Armenia from 1997 to 2004 turned out to be very well suited for the energy and composition measurements at the "knee" of the cosmic ray spectrum. The problem of event-by-event classification of EAS has been solved by applying Bayesian and neural network techniques. The main results of MAKET-ANI data can be summarized as follows: The estimated energy spectrum of the light mass group of nuclei shows a sharp knee: $\Delta\gamma \sim 0.9$, compared to ~0.3 for the all-particle energy spectra. The energy spectrum of the heavy mass group of cosmic rays shows no break in the energy interval of 10^{15} – 10^{16} eV. In the new era of EAS studies by HAWK, LHAASO, and other experiments aimed to detect point sources of ultra-high energy gamma radiation (PeVatrons) to solve the millennium problem of cosmic ray origin, it is interesting to present and analyze the full pattern of available energy spectra in the energy range from 10^{13} to 10^{16} eV.

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1. Introduction

In 1997 the MAKET-ANI [1] surface array in Armenia was launched in its full configuration with ~100 plastic scintillators of 1 m^2 area each. The efficiency of extensive air shower core selection from the surface of ~1000 m^2 around the center of the array was above 95% for EASs generated by primary particles with energy $\geq 5*10^{14}$ eV. The compact array with continuously calibrated detectors turned out to be very well suited for the energy and composition measurements at the "knee" of the cosmic ray spectrum.More than a million EASs detected in 1999-2004 have been carefully examined and used for the estimation of energy spectra of light and heavy nuclei. Using the non-parametric multivariate methodology of data analysis [2], the problem of event-by-event classification of EAS has been solved [3] using Bayesian and neural network techniques. In 2004 for the first time, MAKET-ANI detector presented the light and heavy nuclei differential energy spectra [4].

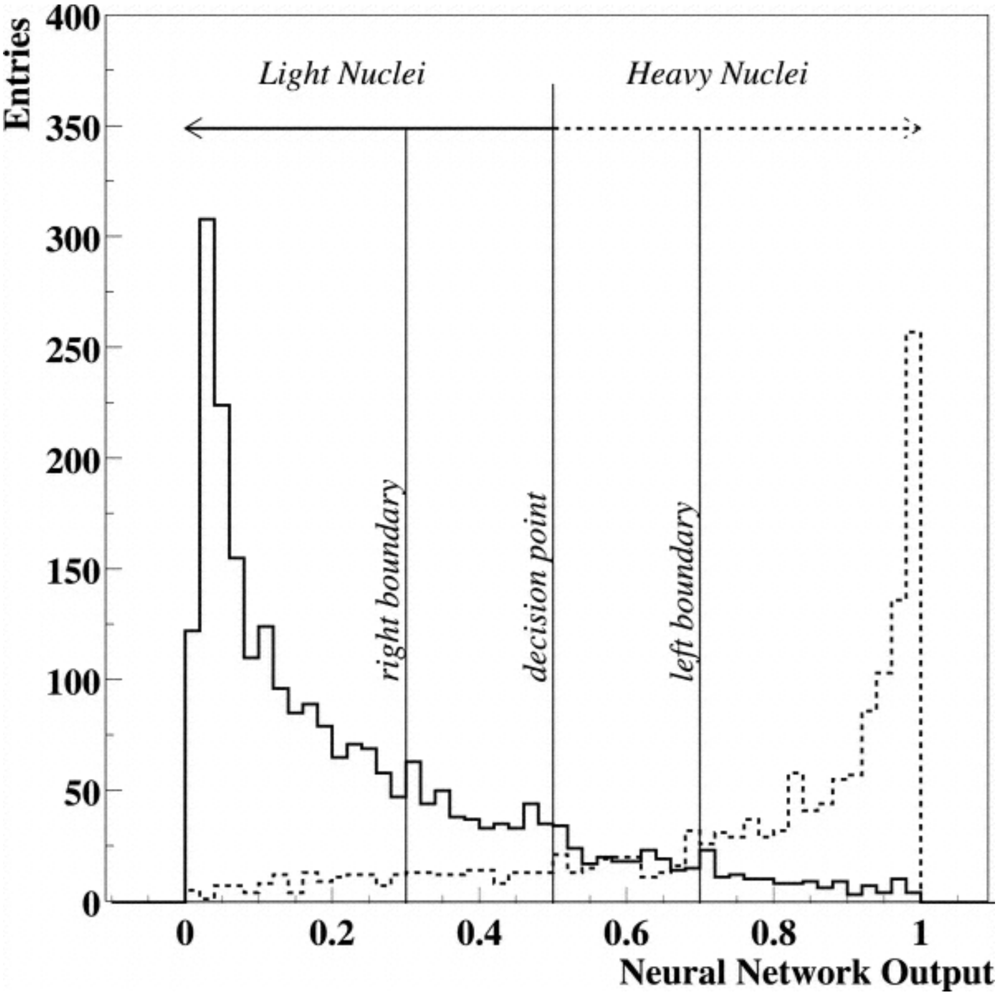

Figure 1. The output of the Neural Network trained to distinguish "light" and "heavy" nuclei (shower age and size were used as input parameters). By vertical solid lines are shown the decision boundaries corresponding to purified selection of primary nuclei (0.3 and 0.7) and to the overall classification into 2 nuclear groups (0.5).

In Fig.1 we show the output of a neural network performed with the ANI package [5]. Network was trained with samples of "light" and "heavy" primary nuclei obtained with CORSIKA simulations. The trained neural network performs a nonlinear mapping of the EAS parameters to the real number interval [0,1]. As we see in Fig.1, trained neural network can be used for the classification of experimental EAS data by defining the boundaries for selecting 2 types of primary nuclei, and possibly a region where no reliable solution can be made. The purity of the samples (fraction of true classified events in an actual sample allocated to a given class) can be noticeably improved without a drastic reduction of the efficiency (defined as a fraction of true classified events of the total number of events of a given class). By choosing the boundary we can "purify" the selected light and heavy nuclei samples. Sure, we have to decide on the trade-off between the purity of the selection and the efficiency of EAS registration. The purity and the efficiencies are obtained by classifying 35,000 light (p, He) and 17,000 heavy (O, Si, Fe) control events, which are not used for the training of the neural network. The neural classifier selects the ''light'' component with an efficiency of ≈75%, purity of ≈85%, and the ''heavy'' component with an efficiency of ≈75%, purity of ≈57%.

The physical inference from the MAKET-ANI experiment was made not only by multiple comparisons with CORSIKA simulations but also by regular cross calibrations, checks of efficiency, and uniformity in detector response eventual for retaining stability and reliability of detector operation. All methodic errors were carefully revealed and checked. Excellent agreement of the measured shower lateral distribution with simulation was achieved [6,7].

The main experimental results on energy spectra of light and heavy mass groups measured in the MAKET-ANI experiment provide, as shown in Figure 2, evidence in favor of the rigidity-dependent acceleration at the outer boundaries of SNR:

- The estimated energy spectrum of the light mass group of nuclei shows a very sharp knee: $\Delta\gamma \approx 0.9$, compared to $\Delta\gamma \approx 0.4$ for the all-particle energy spectra.

- The energy spectrum of the heavy mass group of cosmic rays shows no knee in the energy interval of 10^{15}– 10^{16} eV.

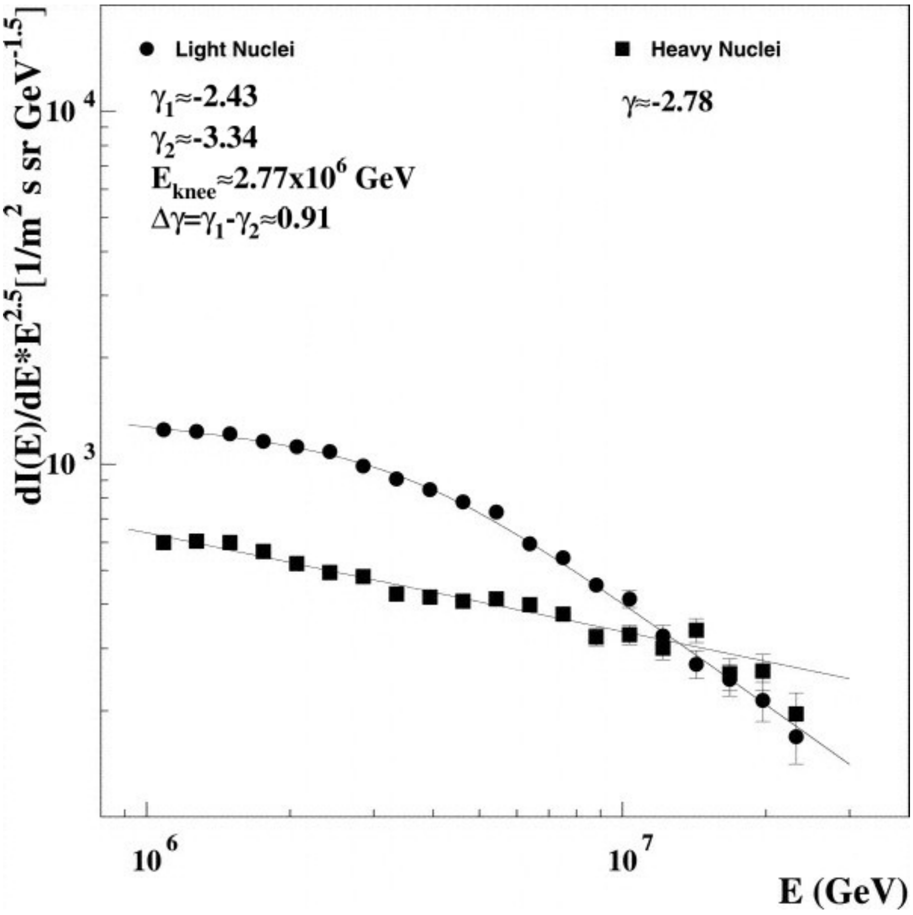

Figure 2 Energy spectra of light and heavy nuclei obtained by neural classification and energy estimation. The EAS characteristics used are shower size and shape (age parameter).

Thus, the MAKET-ANI results are consistent with the rigidity-dependent position of the knee. Moreover, since the obtained primary slope below the knee is rather close to the value expected from the 1st order Fermi-type acceleration mechanism, the experimental results support that mechanism for acceleration of high-energy cosmic rays.' Further results from KASCADE array [8] and the AGILE and Fermi orbital gamma ray observatories, as well as several theoretical extensions of the Fermi mechanism further support MAKET-ANI results.

2. Differential energy spectra of light nuclei (p+He)

Until recently, it was assumed that primary cosmic rays in the low-energy region (up to 100 TeV) are described by a power-law with a single spectrum index ~-2.6-2.7. Energy spectra studies were mostly concentrated in the region of the so-called "knee" of the all-particle spectrum, around - 3-4*10^{15} eV, where the PCR spectrum index changed from -2.7 to -3.1.

Recently, direct measurements with excellent space-borne detectors [9-13] revealed new features in the PCR energy spectra. The energy spectra of protons at energies below the knee cannot be described by a single power law. As we can see in Fig.3, around 580 GeV the spectral index changes from -2.83 to -2.55 (i.e., a reverse break is observed in the CALET data [9]), and in the region above 9.3 TeV the spectral index becomes equal to -2.89. The spectrum derived from the CREAMI-III data [10] in the energy region from 2.5 to ~ 10 TeV can be approximated by a power law with exponent -2.65, and all energies above 10 TeV are systematically below the approximation function: i.e., a "break" in the spectrum is observed.

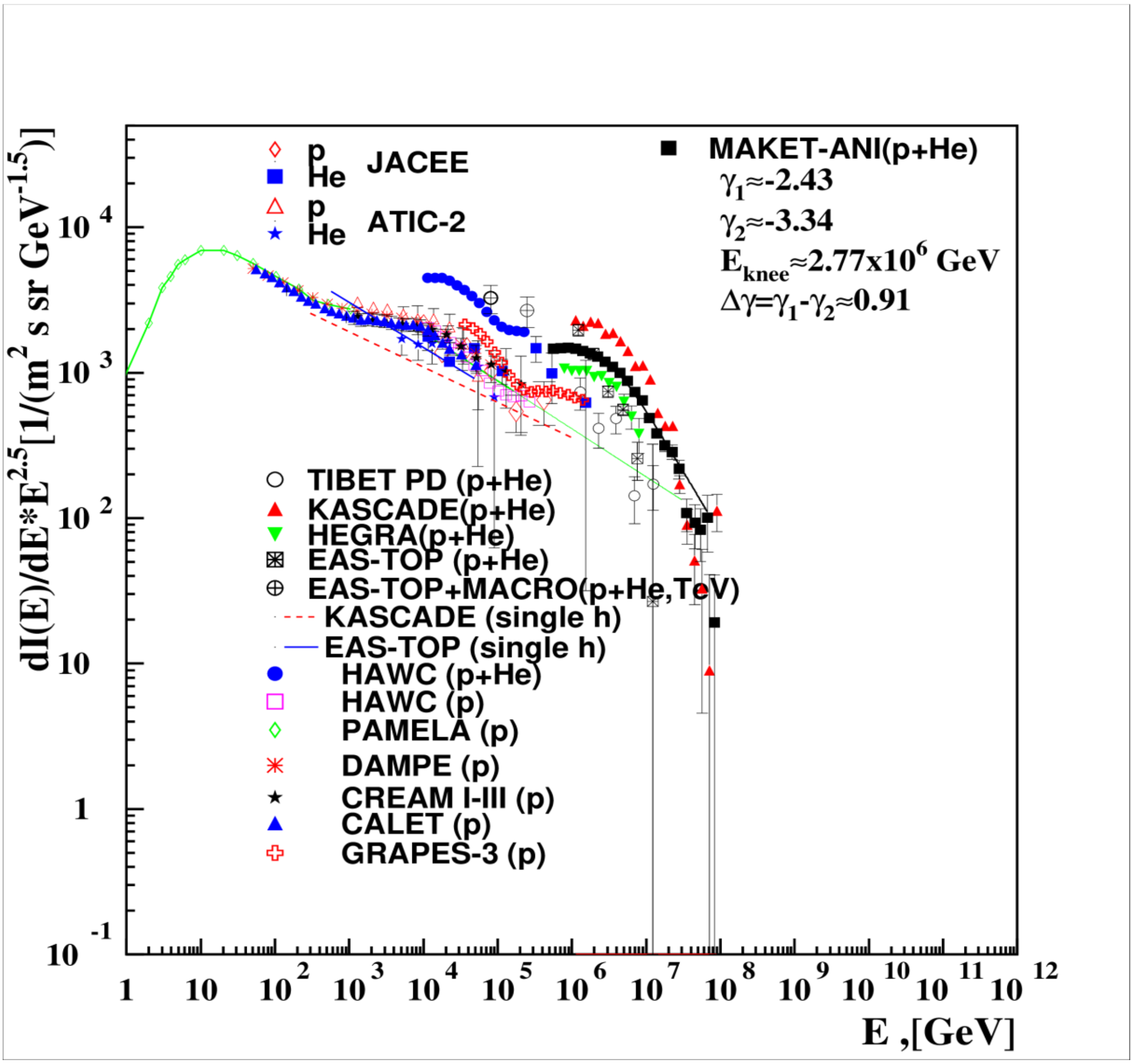

Figure 3. Primary light nuclei (p+He) spectra measured by the MAKET-ANI [1] detector in comparison with the spectra reported by KASCADE, EAS-TOP, HEGRA, EAS-TOP+MACRO, TIBET experiments (all spectra were obtained with CORSIKA QGSJet01model). The direct balloon measurements by ATIC-2 and JACEE are related to the energies of 10^2 - 10^5 GeV (all data taken from [1]). The modern experiments HAWC [12], PAMELA[13], DAMPE[11], CREAM I-III[10], CALET[9], GRAPES-3 [14] are included as well.

In the energy spectra derived from DAMPE [11], HAWC[12], PAMELA[13] , CALET[9], CREAMI-III [10], a knee is observed in the energy spectrum of primary protons around 10 TeV. This situation has already been considered in the framework of several theoretical models in search of a consistent pattern of cosmic ray acceleration (eventually including new sources), and propagation (or reacceleration) in the Galaxy. Recent theoretical models were presented at the International Cosmic Ray 2021 conference [15].

The light component measured by the MAKET-ANI array, quite accurately agrees with the HAWC(p+He) spectrum. However, the fluxes of protons and helium measured by HAWK are equal, which contradicts the “normal” composition of primary cosmic rays in the energy range of (10^{14} -10^{15} eV). Possibly, because of incorrect primary nuclei classification, in the entire particle spectrum, HAWC gives a ≈ twofold increase in intensity compared to MAKET-ANI, KASCADE, EAS-TOP, and HEGRA. However, the proton component of HAWC agrees well with the PAMELA, DAMPE, CREAM I-III, and CALET measurements. According to the CREAM I-III data, in the energy range of 1.0 – 60 TeV/nucleon, the average p/He ratio is estimated at ~9.6. The “reverse kink” in the proton spectrum is also observed in the GRAPES-3 data [14] in the energy region of ≈ 200 TeV.

Conclusions

Measurements of the CR energy spectra from 10 TeV to 1000 TeV with EAS arrays are scarce due to the higher energy threshold (usually above 1000 TeV) of most arrays operated in the last century. New detectors located at high altitudes (4000 m and more) overcome this difficulty significantly lowering the energy threshold down to a few tens of TeV. We compare energy spectra observed by a compact array MAKET-ANI (operated on 3200 m, energy threshold few hundreds of TEV) with high altitude EAS arrays. As we show in Fig. 3 proton spectrum cannot be described by a simple power law. The hardening of the spectrum around the TeV region, observed by PAMELA, ATIC, CREAM, CALET, and DAMPE, has now been confirmed by EAS arrays operated on Tibet and Sierra Negra. Data at energies above a few tens of TeV, in contrast, show softening of the energy spectrum, which again changed to hardening in a few hundreds of TeV energy range. The spectrum “break energies” are different for various detectors. Thus, additional measurements, are required for understanding the spectrum behavior. New models, including, simulation of the proton acceleration in the strong winds of young stars in the galaxy plane are required for explaining the rather complicated shape of light nuclei spectrum below the knee of all particle spectrum. The QGSJet-II and QGSJet-III models [15] predicted 10% higher N_e and N_mu. This should impact the energy reconstruction and thereby rescale down the MAKET-ANI spectrum, bringing them closer to the shown in Fig. 3 lower energy proton spectra.

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References

[1] A. Chilingarian, G. Gharagyozyan, G. Hovsepyan, S. Ghazaryan, L. Melkumyan, A. Vardanyan, E.Mamidjanyan, V.Romakhin, and S. Sokhoyan, Study of extensive air showers and primary energy spectra by MAKET-ANI detector on Mount Aragats, Astroparticle Physics, Volume 28, Issue 1, September 2007, Pages 58–71

[2] A.Chilingarian, Statistical Decisions under Nonparametric a priori information, Computer Physics Comunication, 54, 381, 1989.

[3] A.Chilingarian, G.Zazyan, On the possibility of investigation of the mass composition and energy spectra of primary cosmic ray (PCR) in the energy range from 10^{15} to 10^{17} eV using EAS data, Nuovo Cimento C, Serie 1 (ISSN 0390-5551), 14 C, 555, 1991.

[4] A. Chilingarian, G. Gharagyozyan, G. Hovsepyan , S. Ghazaryan, L. Melkumyan, and A. Vardanyan, Light and Heavy CosmicRay Mass Group Energy Spectra as Measured by the MAKET-ANI Detector, Astrophysical Journal, 603:L29-L32, 2004.
[5] A.Chilingarian, Program Package ANI, (User Manual)
http:// http://crd.yerphi.am/ANI_User_Guide_Introduction
[6] S.Blokhin, S.Gazaryan et al., (2005) The Lateral Distribution function of the EAS electrons as measured by the MAKET-ANI detector, Proceedings of the Russian Academy of Science, Physics series, 69, 535-355.
[7] G.Hovsepyan , S.Sokhoyan, et al. The EAS Size Spectra in the "Knee" Region by the MAKET-ANI Experiment, Proceedings of the Russian Academy of Science, Physics series, 65, 1201, 2002.
[8] T.Antoni, WD Apel, AF Badea, et al., KASCADE measurements of energy spectra for elemental groups of cosmic rays: Results and open problems, Astroparticle physics, 24, 1, 2005.
[9] O.Adriani et al. Observation of Spectral Structures in the Flux of Cosmic-Ray Protons from 50 GeV to 60 TeV with the Calorimetric Electron Telescope on the International Space Station. Phys. Rev. Let. 129, 101102, 2022.
[10] Y.S. Yoon,T. Anderson et al. proton and helium spectra from the cream-iii flight. The Astrophysical Journal, 839, 2017.
[11] Q. An et al., DAMPE Collaboration, Science Advances 5, 9, 2019.
[12] J.C. Arteaga-Velazqueza, for the HAWC Collaboration 37th International Cosmic Ray Conference (ICRC 2021) July 12th – 23rd, Berlin, Germany, 2021.
[13] A.M. Galper et al. The PAMELA experiment: a decade of Cosmic Ray, Physics in space, International Conference on Particle Physics and Astrophysics IOP Conf. Series: Journal of Physics: Conf. Series 798, 012033, 2017.
[14] F. Varsi et al. Updated results on the cosmic ray energy spectrum and composition from the GRAPES-3 experiment. 21st International Symposium on Very High Energy Cosmic Ray Interactions (ISVHE- CRI), 2022.
[15] S.Ostapcheko, Cosmic ray interactions in the atmosphere: QGSJET-III and other models, eprint arXiv:2208.05889, 2022.