Study of Cosmic Ray Primaries between 10^{12} and 10^{16} eV from EAS-TOP

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Abstract

The EAS-TOP experiment has been in operation since January 1989 to May 2000 in the study of cosmic ray physics in the energy range between the direct measurements and the "giant" air shower arrays ($E_0 = 10^{12} \div 10^{16}$ eV, including the *knee* of the primary spectrum). The array was located at Campo Imperatore, 2000 m a.s.l., 30^0 with respect to the vertical of the underground Gran Sasso Laboratories, which allowed operation in stand alone mode, and in coincidence with the underground TeV muon detectors (MACRO, LVD). Different detectors and techniques: hadrons, EAS Cherenkov light and TeV muons, e.m., GeV, and TeV muon EAS components, and their correlated analysis, have been exploited, providing measurements in different energy ranges. The resulting scenario of the high energy galactic cosmic radiation concerning the primary spectrum, composition and anisotropies is presented.

1. The detector

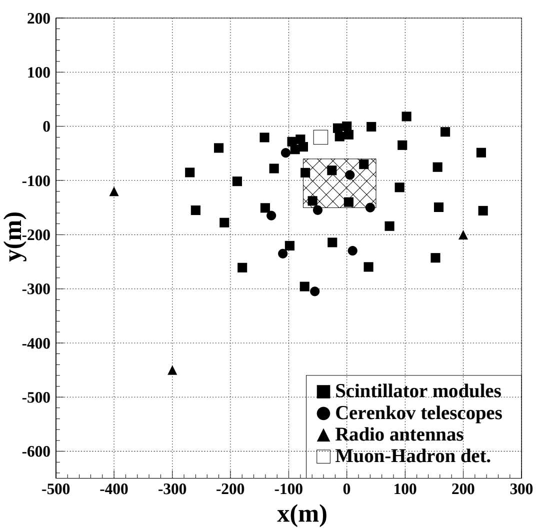

Fig. 1. The EAS-TOP array.

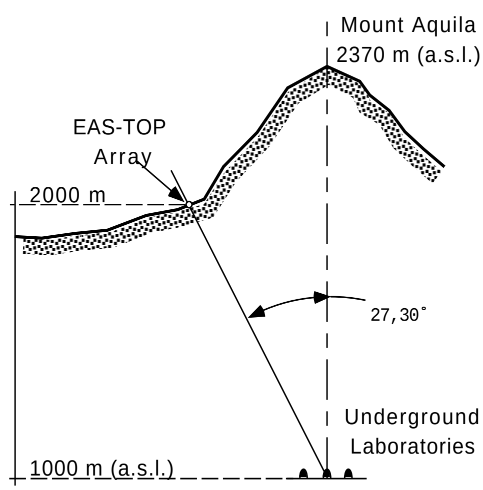

Fig. 2. The EAS-TOP location with respect to the Gran Sasso labs.

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The array configuration, shown in figs. 1 and 2, consisted of: (a) the e.m. detector: 35 scintillator modules, 10 m^2 each, distributed over an area $A_c \approx 10^5$ m^2, for the measurement of the shower size (N_e), core location and arrival direction [4] (main resolutions: $\Delta N_e/N_e \approx 0.1$ and $\Delta\theta \approx 0.5^o$ for $N_e > 2 \cdot 10^5$); (b) the muon-hadron detector: 140 m^2 calorimeter with 9 layers of 13 cm iron absorbers and Iarocci tubes as active elements, operating in "quasi proportional" mode for hadron calorimetry at $E_h > 50$ GeV (energy resolution $\Delta E_h/E_h \approx 0.15$ at $E_h \approx 1$ TeV), and in streamer mode for muon counting at $E_\mu > 1$ GeV [8]; (c) the Cherenkov light detector: 8 telescopes with tracking capabilities loading 0.5 m^2 light collectors equipped with imaging devices (96 pixels each with resolution 1.5 10^{-5} sr) and wide angle optics (7 photomultipliers for a total field of view of 0.16 sr) [3]; (d) moreover EAS-TOP operated in coincidence with the underground MACRO and LVD muon detectors ($E_\mu > 1.3$ TeV; full area $A_\mu^{\rm TeV} \approx 1000$ m^2) [11,12,13]. Data have been analyzed through simulations based on CORSIKA/QGSJET [14,15].

2. Methods and results

A summary of the results on the primary spectrum is reported in fig. 3.
(i) The proton spectrum in the energy range 0.5 - 500 TeV [10] has been obtained from the hadron spectrum measured by means of the calorimeter by taking into account the helium contribution [1,2]. Over the whole energy range it is described as a power law: $S(E_0) = (9.8 \pm 1.1 \pm 1.6^{sys}) \times 10^{-5} (\frac{E_0}{1000})^{(-2.80 \pm 0.06)}$ m^{-2}s^{-1}sr^{-1}GeV^{-1}, in agreement with [1,2].
(ii) The helium and CNO fluxes have been studied from the combined Cherenkov light and TeV muon MACRO measurements at primary energies 80 $\div$ 200 TeV [13]. Primaries are selected through their energy/nucleon by means of the TeV muon information (that further allows the reconstruction of the EAS core geometry with accuracies $\sigma_\theta = 1^o$ and $\sigma_r = 20$ m), while the information on the total primary energy is obtained from the Cherenkov light yield at core distances r = 125 - 185 m. Due to the TeV muon selection, the "p+He" flux at $E_0 = 80$ TeV, and the "p+He+CNO" one at $E_0 = 250$ TeV are obtained. By subtracting the measured proton flux [1,2,10] we obtain: $J_{He}(80 \text{ TeV}) = (12.7 \pm 4.4) \cdot 10^{-7}$ m^{-2}s^{-1}sr^{-1}TeV^{-1}, and $J_{CNO}(250 \text{ TeV}) = (0.24 \pm 0.19) \cdot 10^{-7}$ m^{-2}s^{-1}sr^{-1}TeV^{-1}.
(iii) The all particle energy spectrum is obtained from the measured shower size spectra in the *knee* region [7], showing the angular (i.e. depth) dependence of the *knee* position. The *knee* is observed at $N_e = 10^{6.1}$ in the vertical direction, $E_0 = (2-4) \cdot 10^{15}$ eV (depending on the bending component), and intensity 10^{-7} m^{-2}s^{-1}sr^{-1} with about 20% uncertainty. The obtained power indexes of the energy spectrum are: $\gamma_1 = 2.76 \pm 0.03$ and $\gamma_2 = 3.19 \pm 0.06$ respectively below and above the *knee*.
(iv) The composition analysis at such energies is performed for vertical show-

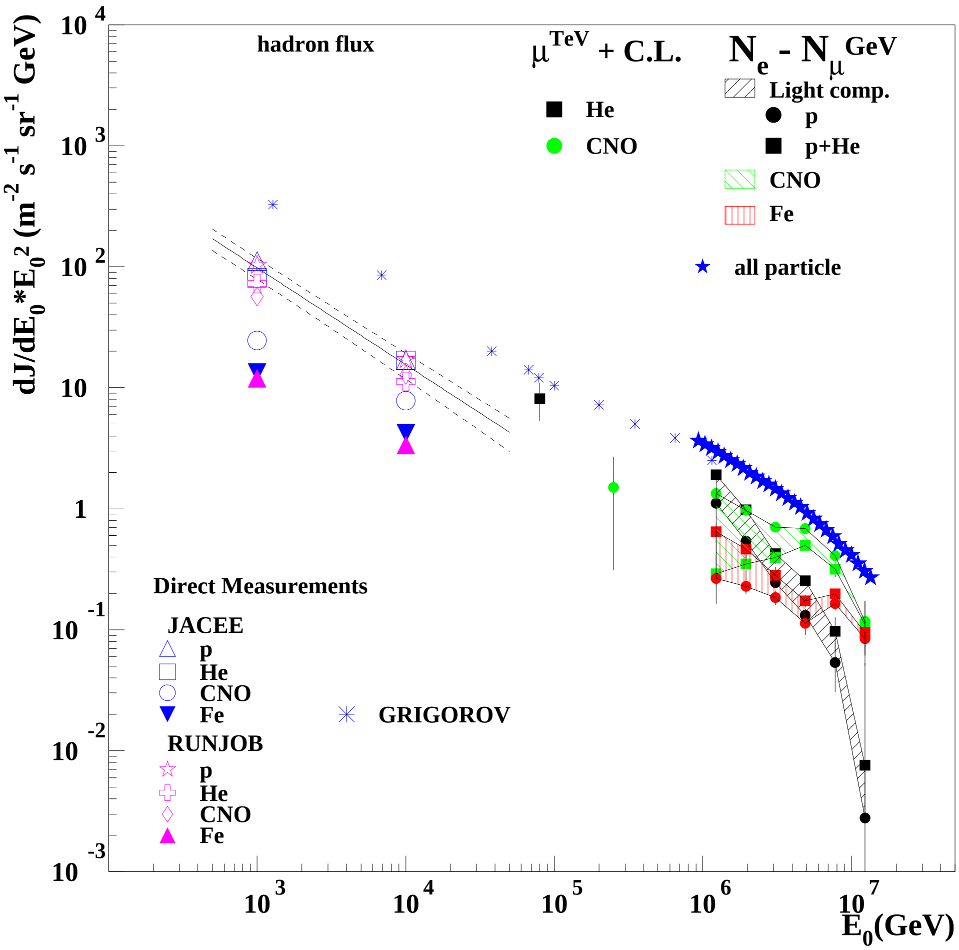

Fig. 3. The Cosmic Ray energy spectrum as resulting from the EAS-TOP data.

ers ($1.00 < \sec\theta < 1.05$) through the shower size N_e and the muon number recorded in the muon detector at core distances r = 180 ÷ 210 m ($N_{\mu_{180}}$). The experimental $N_{\mu_{180}}$ distributions, measured in different ranges of shower sizes ($\Delta Log(N_e) = 0.2$), are fitted with simulated data. Intrinsic fluctuations and measurement accuracies allow a three component analysis: light (constructed either with protons, and a mixture of 50% proton and 50% helium), intermediate (N) and heavy (Fe). The boundaries given in fig. 3 show the obtained evolution of such spectra [9]. $< lnA >$ vs energy evolves from (1.6÷1.9) at $E_0 = 1.5{\cdot}10^{15}$ eV to (2.8÷3.1) at $E_0 = 10^{16}$ eV. The result is analogous to the one obtained in coincidence with the TeV muons observed in MACRO [12], originated from the decays of pions produced in a quite different rapidity region.

3. Discussion and conclusions

The general conclusions can be summarized as follows: (i) the connection with the direct measurements is well described; the proton spectrum obtained from the hadron measurements agrees with the JACEE and RUNJOB ones [1,2], while the He flux is in better agreement with the higher values reported by JACEE; (ii) a consistent picture of the *knee* is obtained in the e.m. and muon (GeV and TeV) components: the break is observed in the spectrum of lighter components (p, He, CNO), not in the heaviest ones (Fe); (iii) data from different observables show good consistency and prove the adequacy of CORSIKA/QGSJET up to the *knee* energies; (iv) the sidereal anisotropy has been measured at average primary energy $E_0 \approx 10^{14}$ eV ($A_{sid,\delta=0^0}$= $(3.7 \pm 0.6)\cdot 10^{-4}$, $\varphi_{sid} = 1.8 \pm 0.5$ h lst): no energy dependent effect, as would be expected from diffusion processes, is observed [6] ; (v) γ-ray astronomy data do not reveal any signal at energies above the "e.m. origin" range [5]. Following the "standard" models of c.r. acceleration, predicting rigidity dependent breaks for the different components (consistent with the present data), a break in the iron spectrum is expected. Its observation requires a measurement extending up to about 10^{18} eV: an array with such acceptance, realized through the re-installation of the e.m. detectors of EAS-TOP, is now starting operation as an extension of KASCADE (KASCADE-Grande)[16].

4. References

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