

WG II Report on UHE cosmic rays

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Abstract. This working group was mainly oriented to discuss experimental results on cosmic rays, from the lowest energies (obtained by direct measurements) up to the highest ones (obtained by extensive air shower indirect measurements). The theoretical contributions concerned the main problems of the modeling of cosmic ray interactions in the atmosphere and of cosmic ray acceleration at astrophysical shocks.

1. Introduction

The main objective of this working group was to give an overview of the experimental results on cosmic rays (CR), in terms of energy spectrum, composition and anisotropies, from the lowest energies up to the highest end of the CR spectrum. With respect to this, there were six talks: a review on direct measurements and one on extensive air showers (EAS) measurements from the PeV to the EeV energy range; three talks presenting the results above EeV by the AGASA, HiRes and Pierre Auger experiments, and one presenting a new technique for measuring CRs in the knee region. From the theoretical point of view, the working group was mainly focused on the problem of modeling CR interactions in the atmosphere, essential to interpret the indirect measurements of cosmic rays (i.e., by means of EAS) at the highest energies. There were two talks: one presenting a review on models of high energy cosmic ray interactions and the other was a status report of the MIPP experiment. Finally, there was a presentation on the general problem of the acceleration of cosmic rays in astrophysical shocks.

2. Overview of the experimental results on cosmic rays

2.1. Direct measurements of cosmic rays (up towards the knee)

Simon Swordy presented a review [?], choosing, in three different energy ranges, results from direct measurements that have implications for the origin and history of CRs:

- In the GeV energy range, he showed the results from the ACE satellite [?] concerning the isotopic composition, for elements with Z up to ≈ 30 and energy ≈ 300 MeV/n. In particular:
 - from the measurements of the abundances of radioactive secondaries (^{10}Be , ^{26}Al , ^{36}Cl , ^{54}Mn) with lifetime comparable with the confinement time, τ , of CRs in our Galaxy, it has been established that $\tau = 15 \pm 1.6$ Myr;
 - from the study of the relative abundances of ^{59}Ni and ^{60}Co (the former can decay to the latter by electron capture: this can not happen if the parent has been accelerated, since electrons would have been stripped off) an estimate of the timescale between

nucleosynthesis and acceleration can be made. From such isotopic ratio it is derived that CRs have spent $> 7.4 \cdot 10^4$ yr before being accelerated;

- from the measurement of the isotopic composition, it appears that this is very similar to the Solar System: a few differences however are apparent (namely for ^{58}Fe), that could be explained by an over presence of Wolf-Rayet stars in the interstellar medium.
- At higher energies (up to ≈ 100 GeV/n) he focussed on the measurements from magnetic spectrometers (BESS [?], CAPRICE [?], AMS [?]) of the fluxes of proton and helium. Even if somehow divergent below a few GeV/n, the three experiments agree in both slope and flux at high energy: the spectral slope seems to be the same and constant, around ≈ 2.75 .
- At even higher energies, (up to 1000 TeV/n, i.e., approaching the “knee” of the CR spectrum, he presented the results from three calorimetry experiments, JACEE [?], ATIC [?] and RUNJOB [?]. A continuation of the low energy spectrum for protons and helium with slope 2.75 seems consistent with RUNJOB data (suggesting a constant magnetic rigidity spectrum). From JACEE, however, protons and helium appear to have different slopes above 1 TeV/n, with an increase of the abundance ratio He/H: ATIC seems to show even a larger effect. The effect on the “mean logarithmic mass” versus energy is that, according to RUNJOB, this is rather constant in this energy region (around 1.5), while for JACEE it is increasing, up to ≈ 2.7 . Such differences are significant and will have an impact on the interpretation of EAS measurements, the only possible ones at higher energies.

2.2. EAS measurements from PeV to EeV

With the talk by **Andreas Haungs** [?] we entered the domain of EAS measurements, in the energy range from PeV to EeV, where the CR spectrum shows one clear change of slope at few PeV, the “knee”, and a much less pronounced (and much more debated) one at a few hundred PeV, the “second knee”. Depending on the scenario, the knee can originate by the diffusion of the CRs (i.e., by a change in the containment efficiency in the Galaxy) or by a change in the acceleration efficiency, or in the acceleration process itself. The second knee in turn can be explained as the knee of the heavy component (expected at the position of the first one scaled with the charge Z or the mass A) or as the crossover between galactic and extragalactic CRs.

- With respect to the knee, he presented a review of the results on the energy spectrum and the mass composition obtained by the KASCADE [?], EAS-TOP [?], EAS-TOP/MACRO [?] and Tibet-AS γ [?] experiments. KASCADE reconstructed the energy spectra of individual mass groups, using unfolding procedures on the experimental data (taking into account both electron and muon size) based on different interaction models. A knee like feature is clearly visible in the all-particle spectrum, as well as in the spectra of primary proton and helium: the knee position varies with the elemental group. The composition is dominated by the light components below the knee and by a heavy one above.

Data from the EAS-TOP array confirm that the knee is due to the decreasing flux of the light component: the analysis has been performed both by correlating shower size with low energy muon densities and with high energy muons (> 1 TeV) measured by MACRO.

The results from Tibet-AS γ are somehow in contradiction. According to them, the flux of the lighter components (H and He) does not bend at the knee, their spectrum being already steeper than from direct measurements. The proton knee occurs below 10^{15} eV, so that at the knee the all-particle spectrum results dominated by a heavy component.

All these measurements depend on the hadronic interaction models used in the analysis. In particular, none of the models is able to describe consistently all the KASCADE data: changing models do not change the shape of the spectra, but the relative abundances only. Finally, in spite of these recent sophisticated experiments and analysis, there are still poor

constraints about the explanation of the knee: in particular the question of mass or charge dependence of the knee position for the different primaries is still without answer.

- With respect to the “second knee”, the main experimental information comes from the study of the composition. On this topic, we expect important results from the new arrays, which have just started their data taking, or are in a construction phase, such as KASCADE-Grande [?], and IceCube/IceTop [?]. The former represents an extension (by a factor 10 in area) of the KASCADE array (including the former EAS-TOP scintillators); the latter (under deployment at the South Pole) will allow to measure in coincidence the shower size and high-energy muons detected under-ice for mass composition studies.

Still about CR measurements at the knee, there was a talk by **Scott Wakeley** [?], who presented a new experimental method, aimed to combine the precision of direct measurements with the effective area of indirect ones. This is based on targeting the Cherenkov light produced directly by the primary cosmic ray prior to its first interaction in the atmosphere. The principle is to measure simultaneously the direct Cherenkov light (whose yield is independent of energy, and has a quadratic dependence on the primary charge, allowing a high accuracy in Z), and the Cherenkov light from the shower (directly related to primary energy, and produced over a large area). The main experimental difficulty is in identifying the different regions of production of the two kinds of light (much higher for the direct one). From the detector point of view, this requires excellent angular and temporal resolution, exceeding even the ones of the current Cherenkov arrays. Even so, the HESS detector [?] could detect this direct light together with the shower one. The technique is at the very beginning, but it is worth while to follow it.

2.3. EAS measurements from EeV to the end of the CR spectrum

The energy region around and above 10^{18} eV is extremely interesting. On the one side we expect that galactic sources of CRs lose dominance, and extragalactic ones take over: in the so called “ankle scenario” the transition should take place around 10^{19} eV, while in the “dip scenario” the transition happens at energies roughly one order of magnitude below. Depending on the scenario, different shapes of the spectrum are predicted, as well as different mass composition and anisotropies: measurements in this region are thus important for discriminating between models. On the other side, due the attenuation of the CR flux caused by photopion production on cosmic microwave background photons, the Greisen-Zatsepin-Kuzmin cutoff in the spectrum is expected at $\approx 10^{20}$ eV, but it is still observationally uncertain: two high exposure experiments (AGASA and HiRes) reveal discrepancies, which the Auger array has been designed to clarify.

The sequence of talks on EAS measurements around (and above) EeV started with **Bruce Dawson** [?], who presented the Pierre Auger Observatory, with a special focus on its plans for measurements around 10^{18} eV. The experiment [?] (under construction in Argentina, and already collecting data since January 2004) has as main focus the study of CRs with energy beyond 10^{19} eV (the Auger results at these energies have presented in the plenary session [?]); it is a “hybrid” detector which combines an array of 1600 water Cherenkov detectors with four fluorescence telescopes, covering an area of 3000 km^2 . The experiment however also offers opportunities to push down the energy threshold to around 10^{18} eV. Both the components (surface and fluorescence detectors) can provide significant aperture even at these “low” energies: the surface detector trigger, based on the coincidence of three water tanks, is indeed fully efficient down to $3 \cdot 10^{18}$ eV. With respect to the “hybrid” aperture, only one water tank is required for providing a constraint on the fluorescence reconstruction of the shower: the single-tank threshold is clearly lower, and high quality hybrid data is available down to $10^{17.5}$ eV. Even at these low energies, the angular resolution is better than 2.2° , the energy resolution $\approx 20\%$, and the resolution in depth of the shower maximum of about 40 g/cm^2 . The most important “low” energy study undertaken so far by Auger has been the search for anisotropy around the Galactic Centre [?]:

despite much improved statistics compared with the AGASA and SUGAR analysis (which made positive claims in the past), no excesses were observed.

Chad Finley [?] presented a review on the most recent results obtained by the HiRes experiment. This is a fluorescence detector that has operated in Utah until March 2006, consisting of two “eyes”: monocular observations currently provide the largest exposure for measuring the cosmic ray spectrum, while stereo observations provide the sharpest angular resolution for searching for small-scale anisotropy (angular resolution $\approx 0.6^\circ$).

- With respect to the spectrum, he showed the results using the monocular datasets. The observed spectra cannot be fitted by a simple power-law: allowing one break point, the fit to the data becomes better, and allows to find the “ankle” of the spectrum (i.e., a hardening) at 4 EeV. From the final fit, with two break points, a cut in the spectrum is found at 60 EeV, which would correspond to the expected energy for the GZK cutoff.
- Concerning the search for possible sources of CRs, he showed the results of a search for correlations with BL Lacertae objects (a subclass of blazars, which are active galaxies with the jet axis pointing almost directly along the line of sight). Previous claims by AGASA and Yakutsk (above 40 EeV) have been tested with the HiRes data, and have not been confirmed. However, the 271 published HiRes events above 10^{19} eV were recently analyzed in [?], and correlations with a sample of 157 BL Lacs with optical magnitude $m < 18$ were found: in this case, the energy threshold for HiRes is lower than in the previous claims, thus it can only be confirmed with independent data from HiRes itself. Before proceeding to the analysis of the new dataset, the collaboration has optimized cuts on the old dataset and the source sample, such as removing the cut in energy, and including also the high-polarized BL Lacs. Such prescriptions has been made then public [?]: the independent dataset amounts to 70% of the previous one, and the new analysis is in progress.

The review on the experimental results was concluded by **Masahiro Teshima** [?] who presented the final results from the AGASA experiment. The AGASA scintillator array (covering an area of 100 km^2) has been operated since 1991 to January 2004 in Japan, with the aim of studying CRs above 10^{18} eV. The energy estimator is the density of particles at 600 m from the shower axis, $S(600)$, determined by fitting a lateral distribution function (LDF) of observed particles to an empirical formula. The relation for the conversion of $S(600)$ to primary energy is evaluated by a Monte Carlo simulation. The attenuation of $S(600)$ with the atmospheric depth is experimentally estimated, through the equi-intensity cuts on the integral $S_\theta(600)$ spectra. The energy resolution is around 30% above $3 \cdot 10^{19}$ eV and 25% above 10^{20} eV. The energy spectrum obtained with the whole dataset (corresponding to an exposure of $\approx 1600 \text{ km}^2 \text{ yr sr}$) shows an extension up to a few times 10^{20} eV, without the expected GZK cutoff [?]: 11 events have been observed above 10^{20} eV, versus 1.3-2.6 expected if the GZK cutoff were present. Teshima presented a critical review of the energy estimation and spectrum: the calculation of the acceptance and the determination of the formula for the LDF have been revisited. These two factors do not induce any difference in the final result. The most important point that he showed is the new estimation of the attenuation curve of $S(600)$: using a new Monte Carlo (based on Coriksa) or the real data from the experiment induces a systematic difference of 10-20%, with an underestimation when using the simulation. This induces a large effect on the spectrum: the energy shifts to lower values ($\approx 10\%$ at 10^{19} eV and $\approx 15\%$ at 10^{20} eV). Thus the number of events above 10^{20} reduces to 5-6; the spectrum becomes rather featureless, with a slope very near to 3, and the flux difference between AGASA and HiRes becomes less significant.

3. Cosmic ray interactions: models and measurements at accelerators

At VHE CRs measurements are based on the air shower technique: to extract informations about energy and particle type, simulations of EAS using electromagnetic and hadronic models

are necessary. These show uncertainties mainly due to hadronic interaction models, and from the extrapolation to energies much higher than those available at colliders.

The talk by **Sergey Ostapchenko** was indeed dedicated to review the present status of the theoretical description of VHE hadronic interactions. The main challenge for models (all of them based on the concept that hadronic collisions are mediated by multiple parton cascades) is the treatment of the regime at high energy and small impact parameters. Indeed in this region, with increasing energy, the collisions are more and more dominated by the contribution of “semi-hard” processes (i.e., parton emission with large momentum transfer and production of hadron jets with high p_t), where the presence of a large number of packed partons results in significant non-linear effects. As of today, several interaction models are available for the CR community, based on different theoretical approaches, the most known being:

- QGSJET [?] , based on the Pomeron phenomenology and describes hadronic multiple scattering as exchanges of Pomerons (i.e., microscopic parton cascades). The latest version (QGSJET-II) treats non linear parton effects as Pomeron-Pomeron interactions.
- SIBYLL [?], also employing Pomeron formalism for the description of soft processes. The “semi-hard” ones are treated in the framework of “mini-jet” approach, orthogonal to the one used in QGSJET-II;
- EPOS [?], based on the soft and semi-hard Pomeron scheme; non linear effects are described by a treatment of lowest order Pomeron-Pomeron interaction graphs.

The parameters of hadron production most important for EAS are the inelastic cross section, the inelasticity of proton-air interactions, the secondary particle production related to the production of the muon component. The predicted inelastic cross section is in reasonable agreement at colliders energy range, while diverge at the highest energies, the largest values coming from SIBYLL. On the other hand, predictions for the inelasticity differ significantly at all energies: an important test will come from the LHCf experiment that will measure neutron spectra in p-p collisions, while the high energy behavior of the p-p cross section will be provided by the LHC measurements. Concerning the muon component, with respect to the inclusive muon spectra, SIBYLL and QGSJET-II are in agreement with the accelerator data (e.g., NA49). For what concerns the EAS muon content, the differences between SIBYLL and QGSJET-II are at 10-15%, while EPOS predicts a much higher number of muons. If this will be supported by EAS data, it could lead to a revision of the present results on CR composition in the knee region.

The energy region important for muon production (10-100 GeV for the hadron parent) is covered by fixed-target experiments employing a proton beam, where the forward region of the phase space of secondary particles is accessible and nuclear targets can be used. **Nickolas Solomey** [?] presented the status of Fermilab MIPP experiment that just completed data taking; an upgraded version of this experiment is currently proposed, collectively covering 1 to 120 GeV/c on multiple targets (Be, C, Cu, Ar, Bi and U) for six beam species (pion, kaon, protons and their antiparticles). Compared to the HARP experiment [?], that has released results on spectra of secondary pions in p+C collisions with a beam momentum of 12 GeV/c, the MIPP one is expected to deliver results for higher momentum beams. The data analysis is in progress.

4. Cosmic ray acceleration: astrophysical shocks

The detection of cosmic rays up to 10^{20} eV emphasizes the problem of the acceleration of charged particles up to such extreme energies; however, even at lower energies the most credible sources of galactic CRs, the supernova remnants, have the same problems in accelerating particles up to the knee energy. In this field, impressive developments are taking place in the study of particle acceleration at shock waves. In the working group, **Pasquale Blasi** [?] presented a talk on a non-linear theory of particle acceleration at astrophysical shocks. The basic mechanism

for acceleration, i.e., the Fermi mechanism, is based on the energization of charged particles in moving magnetized media: a first order efficiency is achieved in the presence of a shock front. In the linear theory, the accelerated particles, having negligible number and energy density with respect to the shocked fluid, cannot exert any reaction on it. For the acceleration process to be efficient however, it is necessary to include non-linear effects, and Blasi described the mathematical theory of particle acceleration at non-relativistic shock fronts with dynamical reaction of accelerated particles and self-generated scattering waves. With respect to the former, the pressure of the accelerated particles modify the shock itself (slowing it down), which in turn modifies their spectrum. This one is no longer a power-law (as it is in the linear case): it rather results to be concave, steeper at lower energies than at higher, due to the different compression experienced at different particle momenta. Even so, the maximum energy of the accelerated particles is exceedingly low, unless a substantial amount of magnetic scattering is present: this can be generated by a second non linear process, i.e., the self-generation of magnetic waves. In this way, the streaming instability of CRs would generate perturbations (amplification) of the magnetic field which in turn would modify the diffusion itself of the particles. The field amplification leads always to an enhancement of the maximum achievable momentum.

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