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High energy astrophysics and high-altitude laboratories(*)

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Summary. — These are some summary remarks given at the Chacaltaya meeting on cosmic ray physics, held in La Paz (Bolivia), July 23-27, 2000. The meeting covered a wide range of topics in cosmic ray physics and high energy astrophysics. This contribution briefly touches on some of the highlights of the meeting, and discusses the important role that high-altitude laboratories can have in the future of these fundamental fields.

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1. – Introduction

The field at the intersection of high energy astrophysics, cosmology and particle physics has had some remarkable developments in the last decade, and the perspectives for the future are of extraordinary interest. This has been witnessed by the interest and richness of this meeting that is clearly impossible to summarize. The fields of high energy astrophysics and particle physics were born together in the first decades of 1900 with the study of cosmic rays. Soon it was realized that for experimental studies there was a big advantage in going to high altitude. The site of Chacaltaya with an altitude of 5200 meters (well above the Mont Blanc level) but easily reachable from the city of La Paz, was soon recognized as an extraordinary site. The most remarkable result achieved in this laboratory was perhaps the discovery of charged pions as tracks in nuclear emulsions exposed during the 40's in Chacaltaya by the group of Lattes, Occhialini and Powell [1]. The two fields progressed together for a while: also the discoveries of the positron, the muon and the strange particles (K's, Λ's) were made in cosmic rays. However soon the research in particle physics moved into the "accelerators era", since with these machines it was possible to obtain precisely known and more intense beams of high energy particles.

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These developments lead to rapid progress that finally culminated in the extraordinary synthesis of the "Standard Model". On the other hand, in spite of great experimental efforts, a full understanding of the origin of the cosmic rays remained elusive. The last decade however has seen a remarkable progress in our understanding, with a fundamental contribution due to the development of γ-astronomy, that has allowed the unambiguous identification of some astrophysical sites where violent non-thermal processes are happening and high energy radiation is emitted. In the next decade, we are likely to see great progress, thanks to several very promising experimental projects, in new measurement of cosmic rays (especially at the highest energies), new detectors in γ-astronomy, and the deployment of high energy neutrino telescopes, with the sufficient size (~ 1 km^3) to really detect the expected astrophysical ν-fluxes. Also gravitational wave studies will hopefully contribute to our understanding of the "violent universe". An exciting possibility is that the fields of high energy astrophysics and particle physics will again come together, with "fundamental physics" receiving important inputs from the experimental studies of the astrophysical high energy radiation. The experimental program of the next decade will be very diverse, with for example ν-telescopes placed 4 km deep underwater (or 2 km under-ice), or γ and cosmic rays detectors placed on satellites (or on the International Space Station) in near Earth orbits. The role of laboratories placed at high mountain altitude (4000–5000 km) will however remain important, since several experimental programs, in particular ground-based γ-astronomy and studies of cosmic rays in the "knee" regions, are best performed at this altitude. For these studies the Chacaltaya laboratory will remain one of the very best available sites.

2. – γ-astronomy

High energy γ-astronomy ($E_\gamma \gtrsim 1$ GeV) has emerged in the 90's as a mature, vital, and highly interesting field (for recent reviews see [2-5]). The most significant development has been the launch in 1991 of the *Compton Gamma Ray Observatory* (CGRO) with aboard its four instruments. The satellite remained active until June 2000 when it was deorbited. The highest energy detector EGRET (detecting photons in the energy range ~ 30 MeV–30 GeV) has produced a wealth of astrophysical results, collecting a catalogue with over 270 point sources of γ-rays [6]. The space-based detectors have been complemented by ground-based atmospheric Cherenkov telescopes (ACTs), which detected γ-rays with energies above 250 GeV from a few sources. The observation of the Crab Nebula first by the Whipple detector, and confirmed by several others, has firmly established ground-based γ-ray astronomy on a solid foundation [3]. The number of detected TeV sources is much smaller than the EGRET catalogue and consist of only a handful of objects, the Crab, a young supernova remnant SN1006, the pulsar PSR_1706-44 and three extragalactic objects, the blazars Mrk 421, Mrk 501 and 1E2344+514. A simple extrapolation of the EGRET spectra predict flux levels that are above the sensitivity of the existing telescopes. The most likely explanation for the non-observation of these sources is the absorption of the photons in the propagation over extragalactic distances for the process $\gamma\gamma \to \mathrm{e}^+\mathrm{e}^-$ with background (infrared: $\varepsilon \sim 0.5$ eV) photons. The spectral cutoff for this process should be ~ 50–200 GeV, and therefore it becomes particularly important to explore the energy range between the ranges covered by satellites and the TeV region.

The majority of the sources away from the galactic plane have been identified as active galactic nuclei (AGN), essentially all of them of the "blazar" class. AGN's are currently understood as objects where the gravitational energy of material accreting on a massive black hole powers the emission of jets where plasma is emitted with relativistic speed. The blazars are those objects where one of the jets points close to the direction of the line of sight. The most commonly accepted explanation for the emission of high energy photons is a combination of i) the acceleration of electrons and positrons at the shocks produced in the plasma flow; ii) emission of synchrotron photons from this population of high energy $e^{\pm}$; iii) generation of higher energy photons with inverse Compton scattering (the process $e^{\pm} + \gamma_{\rm soft} \rightarrow e^{\pm} + \gamma_{\rm hard}$). This general mechanism predicts a spectrum with two broad "bumps" that correspond to photons produced in the two processes. It remains open the possibility that not only leptons, but also (or perhaps even prevalently) hadrons are accelerated in these objects. In this case one would have an additional source of photons, that is the decay of the π^0 produced in the interactions of the accelerated hadrons with a target that would be probably due to the high density radiation fields present in the source. In this case AGN's could provide the source of the highest energy cosmic rays; moreover they could be a very attractive source of high energy neutrinos that would be produced after the decays $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$ and charge conjugate channels. Since the cross-sections for the productions of π^+, π^- and π^0 are related by isospin symmetry, and are approximately equal, one can use the experimental results on the photon fluxes to estimate, taking into account the different absorption of photons and neutrinos in the source and during propagation, to predict the expected neutrino fluxes. Currently neutrino detectors with a size of around a cubic kilometer in water or ice are under development [7]. If these "proton blazar" ideas are correct, then they will have a very good chance to measure these neutrino fluxes.

Gamma Ray Bursts (GRB), first recorded by the VELA satellites in 1967, are bright transients events in the γ-ray sky, with a typical duration of $\sim$ seconds. The study of gamma-ray bursts has been one of the most fascinating topics in astrophysics, with several striking results established recently (for more extensive reviews see [8]). Two breakthrough observations were made in this decade. First the BATSE detector [9] aboard the CGRO could detect approximately 1 burst/day, and showed that the events are perfectly isotropic, but dishomogeneous, pointing to a cosmological distribution. Then after the X-ray satellite Beppo-Sax [10] allowed to measure the positions of the events with a better resolution (error boxes of one arc-minute), and this allowed the discovery of the afterglow and detailed multi-wavelength studies. The extragalactic nature of these objects is now unambiguosly established. Looking at the images of the development of the fireball produced by a nuclear explosion in the atmosphere and its evolution into a nuclear "mushroom" we can understand that there was an explosive release of energy in a very short time and a very short volume, however without additional measurements we cannot deduce from these images what was the energy source of the explosion. Similarly in a gamma-ray burst, and the following afterglow, we are looking at an extraordinary explosion, with the release of a truly astonishing amount of energy (10^{51}–10^{54} ergs) in a time much shorter than a second. The determination of the source of this energy, and of the mechanisms that transform this energy into the ultrarelativistic fireball that we observe will certainly be one of the most fascinating topics of the next decade. They have also been identified as possible sources of the highest energy cosmic rays and of detectable fluxes of neutrinos.

3. – The "knee" of the cosmic ray spectrum

Since the time when it was realized with the experiment of Victor Hess at the beginning of this century that a flux of ionizing radiation was reaching the Earth from outer space, the origin and nature of the "cosmic radiation" has been an outstanding problem in physics, that in fact, in spite of a century of experimental and theoretical efforts, remains still very open. The difficulty of the problem originates from the quasi-complete lack of angular information, since the directions of charged particles are scrambled because of the bending in the interstellar magnetic fields, and also because of the smoothness of the energy spectrum, that appear a nearly perfect, featurless power law: $\phi(E) \sim E^{-\alpha}$, over ten decades of energy (from 10^9 to 10^{20} eV). The two most prominent structures are the "knee" at an energy $E_{\text{knee}} \sim 3 \times 10^{15}$ eV and the "ankle" at $E_{\text{ankle}} \sim 5 \times 10^{18}$ eV. At the knee there is a steepening of the cosmic ray spectrum from $\alpha \simeq 2.7$ to $\alpha \simeq 3$, while at the ankle the spectrum becomes again flatter. The ankle can be simply understood as the emergence of a harder component (perhaps extragalactic) over a softer (galactic) component. This natural interpretation is supported by indications that the composition is changing in a way that is consistent with this hypothesis, assuming that the galactic component is "heavy" (iron rich) and the new component is light (proton dominated).

While evidence for the existence of the "knee" in the spectrum has been obtained already from measurements of the shower size spectrum in the 50's, the reasons for this steepening remain unclear. It would be of great help if the energy spectrum and the changes in mass composition were measured more accurately. Significant progress has been obtained in recent years, however the problems are far from solved (for a review and references see [11]). A crucial advantage of mountain altitude measurements is that the showers in the knee energy range reach the maximum development close to this level, and therefore measurements at this level have the smallest possible statistical errors. A key requirement for the detectors is redundancy [12], with the simultaneous measurement of different quantities: the electromagnetic size (number of electrons, positrons and photons), the number of muons, the number and energy spectrum of the hadrons, and the Cherenkov light signal. A fundamental problem is the fact that to pass from the shower observables to an estimate of the primary energy and mass one requires a Montecarlo calculation, where particles are followed stochastically with assumptions being made about the particle physics properties of the interactions.

4. – Hadronic interactions

Hadronic interactions have been another of the major topics of this meeting. At a fundamental level these interactions are described by the QCD (Quantum Chromo Dynamics) Lagrangian, that has as fundamental objects quarks and gluons. However we do not understand confinement, and we cannot compute from first principles properties of the interactions, such as the values of the cross-sections, the multiplicity of final state particles, their energy spectra, and so on. This is a very important problem for cosmic ray studies, indeed it is *the* problem for all "indirect" methods, where one detects not the primary particle itself but the shower that it develops.

One could hope that even without a deep understanding of the properties of fundamental interactions, it could be possible to use the existing data to construct an accurate "phenomenological" description of the interactions. Unfortunately this phenomenological description, while of great value, is not sufficiently accurate for many purposes. The simple reason being the fact that the available data are not sufficiently extensive and accurate. The existing data do not cover the entire energy range that is needed, since the highest c.m. energy obtained ($\sqrt{s} = 1.8$ TeV at the Fermilab collider) corresponds to a laboratory energy $E_0 \simeq 1.7 \times 10^{15}$ eV just below the "knee". The situation is actually significantly worst than this simple estimate indicates, since at a collider it is possible to study only a very small fraction of the phase space. In fact the average transverse momentum of the final state particles is small (of order ~ 0.5 GeV), and therefore only very soft particles are produced at a sufficiently large angle to be detected even in very large acceptance detectors. These soft particles are produced abundantly, but carry only a small fraction of the energy of the interactions. The higher energy particles that are emitted at small angle, and go undetected are the most important ones in the development of showers.

QCD can be a guide to estimate both the energy dependence of the cross-sections and the evolution of the properties of particle production with increasing energy. This field is known with the names of “Pomeron physics” or “Regge-Gribov” calculus (see [13]). As an important example, in the community of cosmic ray physicist, the quantity $\langle E_{\rm leading}\rangle/E_0$, that is the average fraction of the primary energy of the projectile particle (in the laboratory system) carried away by the “leading nucleon” is called the “elasticity” of the interaction, and correspondingly the energy carried by the other particles in the final state is called the “inelasticity” (or K). It is easy to see that the inelasticity is important in shower development, and therefore in the interpretation of shower observables. If the inelasticity decreases and the leading particle carries more energy, the showers will be more penetrating. From QCD (and the Regge-Gribov calculus) one predicts that the inelasticity increases with the primary energy. Qualitatively one can picture this as the consequence of the growth with energy of the number of elementary interactions that the parton components (quarks and gluons) of the projectile particle undergo during the crossing of the target. However this expected behaviour has not been clearly established experimentally. The collider data do not give unambiguous answers, since the leading particle is emitted at very small angles and is not detected in most of the events. In this respect it is important to note that data from emulsions chambers placed at mountain altitude show on the contrary a decrease in the inelasticity with energy.

I would like to observe that the study of “soft hadronic” interactions should be considered as a very important subject in particle physics that deserves a dedicated experimental program. It is fair to say that the entire community that works on cosmic ray research would consider a more extensive experimental program on “minimum bias” hadronic interactions at LHC as very desirable. The experimental challenges are very difficult, since it is necessary to measure particles emitted at very small angles with respect to the beam direction (see for example [14]), but nonetheless a dedicated program could yield data very valuable for the interpretation of the measurements of high energy cosmic rays.

4˙1. *Centauro events*. – Emulsion chambers placed at mountain altitude allow to observe in great detail the hadronic core of high energy showers when it is still “young” in its development [15]. For nearly 30 years there have been some puzzling and fascinating results about the possible detecton of “exotic” events in emulsion chambers. The most famous category of these events are the so-called “Centauro events” [16]. The interpetration of these events, roughly speaking can come from three directions: they could be extreme fluctuations of standard physics, they could be the effect of the onset of some new phenomenon like for example the existence of “disoriented chiral condensate” [17], or they could be the product of some new particles arriving with the normal cosmic rays. My personal opinion is that these claims should be considered with a healthy dose of skepticism, and that it is possible that with a better understanding of the detectors, and a better modeling of the fluctuations of the “standard physics”, it will be possible to explain these events without requiring the existence of new effects and particles, however it is certain thet they deserve very careful and detailed additional studies.

5. – The "end" of the cosmic ray spectrum

The cosmic rays above the ankle and up to the highest energy have become one of the most important subjects of experimental and theoretical research. A key fact is that the universe is filled with different radiation fields, the most important and best known being the 2.7 K cosmic microwave background (CMB). High energy particles can interact inelastically with these background photons, when they are above a certain threshold. For protons the threshold corresponds to the production of pions (as in $p\gamma \to p\pi^0$ or $n\pi^+$) and is just below 10^{20} eV. This constitutes the so-called Greisen-Zatspepin-Kuzmin or GZK cutoff [18]. Protons with energy above this threshold can propagate for a distance that is only a few tens of Mpc (1 Mpc $\sim 3 \times 10^{24}$ cm is the typical distance between galaxies), that is from relatively nearby, unless something exotic is envisaged. While most physicists expected to detect the GZK cutoff in the spectrum very likely this has not happened. There is evidence from AGASA [19] (a 100 km^2 detector in Japan) that the spectrum is inconsistent with the expected shape of the cutofff (assuming that the sources are uniformly distributed in the Universe). This is reinforced by the results of the Fly's Eye detector, that is based on using the fluorescent light emitted by the showers during clear moonless nights, that has detected an event with an energy solidly estimated at 3×10^{20} eV [20]. These results could have very profound implications and should be investigated very critically to be certain that there are no "loopholes". The answer to these questions can be obtained with the next generation of detectors. The next one is the Auger detector [21] with two sites, each with an aperture of 7000 km^2 sr, and having the advantage of being a "hybrid" detector, combining the two techniques of the air shower array and of the Cherenkov light. At this conference we heard exciting news about the rapid progress of detecting giant air showers from satellite in space observing their tracks of fluorescent light [22].

6. – High energy astrophysics and "fundamental physics"

As discussed in the introduction, particle physics was born with cosmic rays, and then moved to the man-made accelerators. It is fascinating to see that in the future the relation between the two fields could again become very strong. One could talk of two different scenarios for the future. In the first one the connection is direct. There have been several fascinating (but very speculative) ideas that relate the study of the highest energy cosmic rays with fundamental physics (see, for example, [23]). Perhaps the most fascinating is the idea that the highest energy particles are not accelerated ("bottom up" models) but are the decay of metastable ultra-heavy particles (or "objects" like topological defects). In this sense one could note that the energy $E \sim 10^{21}$ eV is not too distant from the energy scale of a possible unification of the interactions $E_{\rm unification} \sim 10^{24}$ eV.

In the second more "boring" scenario the highest energy cosmic rays are simply accelerated in the same sites as the lower energy particles, and the non-observation of the GZK cutoff can be understood as a combination of the effects of the proximity of the sources, statistical fluctuations and resolution effects. This is what I think is by far the most probable scenario, if perhaps not the most desired one by physicists. The point I would like to make is that this "boring" scenario is also nearly certainly going to be also of extraordinary interest for fundamental physics. In this case the natural questions are something like: i) what are the accelerators, ii) how do the accelerators work, iii) how are they made. To obtain answers to these questions, it is very likely that we will have to learn a lot of fundamental physics. As an illustration we can think about the "normal" cosmic rays with energy $E \lesssim E_{\rm knee} \sim 10^{15}$ eV. As discussed before the most likely explanation (even if not really well established yet) is that the bulk of the cosmic rays is accelerated in the blast waves of supernovae. This idea was proposed very early, on the basis of simple order of magnitude estimates about the power necessary to produce the population of cosmic rays that were observed. To put this conclusion on a firmer basis, that is to understand how these accelerators are made and work, it has been necessary to develop many of the fundamental concepts in physics, for example: nuclear fusion reactions (to describe the stellar structure and evolution), quantum statistics (to understand the source of pressure that sustains the iron core in a supernova progenitor before collapse, and the neutron star after the collapse), the equation of state of super dense matter (to understand how the collapse is halted, and the "bounce" generates the shock wave that expels the outer layers of the star), neutrino physics (since neutrinos very likely provide the the final push to the shock wave in its outward propagation before it reaches the progenitor star's surface). The final step of this complex theoretical construction is the Fermi mechanism that describes how charged particles are stochastically accelerated when they diffuse in the complex magnetic field across the propagating blast wave.

The standard supernova blast waves cannot be the sources of the highest energy cosmic rays. This can be understood with simple dimensional analysis arguments, since these objects have a size too small and magnetic fields too weak to confine very high energy particles inside the accelerating region [24]. One has then to find other acceleration sites. It is remarkable that at least two classes of objects: AGN's and GRB's satisfy (at least potentially) the "dimensional" argument of size and field strength for the acceleration of particles up to the highest energies, and could potentially provide sufficient power to generate the population of the highest energy cosmic rays. We still have a lot to understand. It is likely that the general idea of the Fermi acceleration, probably in shock waves moving at ultrarelativistic speed, will again play a role, but it is very likely that to understand the nature of the objects and the physical mechanisms that are at the origin of the plasma flows one will need to learn a lot of fundamental physics, probably having to do with quantum-mechanical effects near the horizons of black holes.

7. – High-altitude observatories

In this meeting, held in the highest capital of the world, a short drive from the highest laboratory in the world, not surprisingly an important theme of discussion has been the importance and the future perspectives of high-altitude (ground-based) laboratories. The interest for these studies appears to be very strong, and the scientific motivations very solid. In fact in brief it is possible to summarize the discussion saying that with the exception of the Auger project, that studies showers so large and penetrating that they keep developing down to sea level depths, essentially all other experimental projects discussed at this conference would clearly benefit from a higher altitude location. Several topics have been identified where the advantage of high altitude is particularly marked:

1. Studies of the cosmic ray spectrum and composition around the "knee', since at this energy vertical showers are close to maximum development at high mountain altitudes, and fluctuations are at a minimum.

2. Studies of the hadronic core of high energy showers. These studies can give information of hadronic interactions, and can investigate the claims of "exotic" behaviour or the existence of new particles in the primary flux.

3. Ground-based astronomy in the energy region that bridges the satellites measurements ($E_\gamma \lesssim 30$ GeV) and the Cherenkov measurements ($E_\gamma \gtrsim 250$ GeV). This energy region allows to study the very high energy emission from the sources, since for higher E_γ the absorption in the fields of background photons via the process $\gamma\gamma \to e^+e^-$ becomes very important.

The highest sites that can be operated continuously are at an altitude just above 5000 meters, as is dictated by human physiology. The detector must be placed near the equator to have reasonable climatic conditions, and for Cherenkov measurements dry, good weather is important. Chacaltaya remains one of the very best conceivable sites, and the vicinity to the city La Paz, makes it exceptionally attractive. Hopefully this potential for experimental studies will be rewarded with new intersting results in the exciting new field of astroparticle physics.

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