Probing theories with cosmic rays

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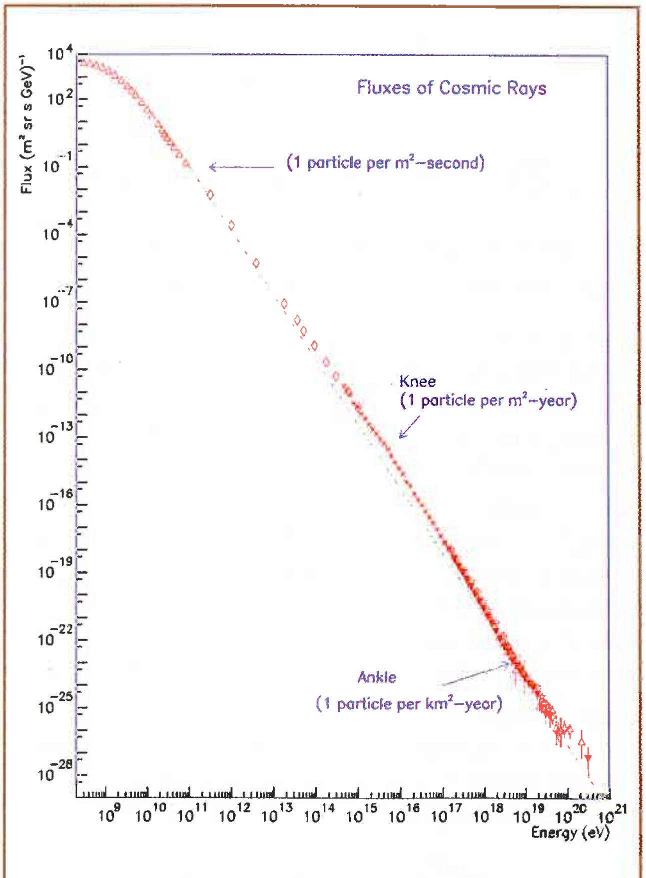
Although most people are not aware of it, our body (or any surface on earth) is crossed by hundreds of particles of cosmological origin every second. These "cosmic rays", discovered almost a century ago (in particular by Victor Hess), are one of the very few means available to an earth based observer to study astrophysical or cosmological phenomena. The knowledge of their incoming direction, their nature and their energy spectrum are the bits and pieces of a complex puzzle which, put together, can give us strong information on the mechanism that produced them at the origin, unfortunately distorted by many effects they can undergo during their journey over large distances. Needless to say that this discipline called "particle astrophysics" or "astroparticle physics" is delicate, difficult and very often controversial.

The cosmic ray energy spectrum (see Fig.1) extends from 1 GeV to somewhat above 10^{20} eV (or 100 EeV, the prefix "E" being for exa, i.e. 10^{18}). Over this energy range the intensity (rate of arrival on earth per unit surface, solid angle and time) decreases by 24 orders of magnitude. It is important to note that at the extremity of the spectrum, the flux becomes very low: one particle/km^2-year above 10 EeV. The energy spectrum is remarkably regular: a simple power law (roughly a E^{-3} dependence). This is actually quite well understood in the framework of the conventional acceleration mechanisms for charged particles. However, although they are barely visible on this figure, there exist at least three irregularities in this otherwise simple form of the spectrum. One around 10 PeV called "the knee", another around a few EeV called "the ankle", and a final one—not visible on this figure but probably the most mysterious of them all—around a few tens of EeV and inevitably called "the toe". The two first structures are not totally understood, but reasonable hypotheses exist as to what is their cause [1]. The last one which appears at the extreme end of the spectrum (see Fig.2) is not understood at all, and it is widely agreed that the answers brought to the many open questions raised by this "toe physics" will no doubt open new windows in the fields of astrophysics, cosmology and/or fundamental interactions [2].



▲ **Fig. 1:** The all-particle spectrum of cosmic rays (from S. Swordy). The arrows and values between parentheses indicate the integrated flux above the corresponding energies.

Mysteries are the staple diet of scientific progress. In the field of particle astrophysics, the ultra-high energy cosmic rays (UHECR: in this article, we'll use this acronym for the cosmic rays with energies around and above 10^{20} eV) have certainly played this role during the past 40 years or so. What makes the UHECR special is that we do not know what is their origin and nature. Many people working in the field use words such as "puzzle", "mystery" or "enigma" as to their origin. It is symptomatic of the unknown nature of the UHECR and of their origin that some authors coined neologisms such as *uhecrons* or the *toenail clippings of the universe* (natural continuation of the "knee", "ankle" and "toe" features of the spectrum) for the particles themselves or *Zevatrons* for the mechanisms at their origin (the ZeV is for "zetta electron-volt" i.e. 10^{21} eV).

Mysteries are the staple diet of scientific progress

There are a few observational facts to prove that the UHECR are indeed a mystery as of today. The fact that their sources (whatever they are) are expected to be in our close neighbourhood and yet we do not see them; that their energy is so huge that no conventional astrophysical acceleration mechanism seems capable of producing them; that during more than four decades of observation we did not succeed in giving them an identity (what kind of particles they are?). Let us shortly develop these three essential points. The interested reader can complete his information through more complete recent reviews [3].

The propagation puzzle: the GZK cutoff

The chemical composition of the UHECR is unknown. However, the number of stable particles which can propagate over cosmological distances without losing most of their energy is quite limited in numbers: heavy or light atomic nuclei, photons and neutrinos. Photons and neutrinos (neutral particles) cannot be accelerated by any conventional (electromagnetic) mechanism: they can only be produced as secondary products in the interaction of a still higher energy charged particle. We'll see below that if photons and neutrinos were to be found as dominant components of the UHECR, then we would be on the eve of one of the most important discoveries of the century. Therefore, in the framework of conventional astrophysics, we are left with atomic (light or heavy) nuclei as the most likely candidate UHECR. A

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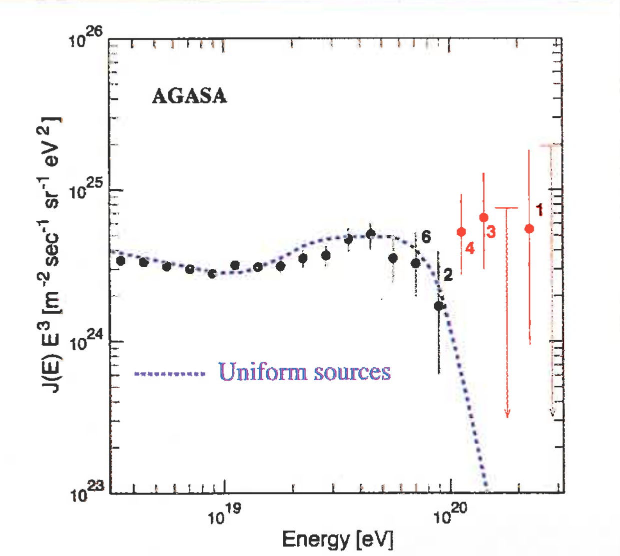

▲ **Fig. 2:** A zoom on the highest energy range of the cosmic ray spectrum (from the AGASA experiment). For better lisibility, the spectrum is made flat by multiplying it by E^3. The dotted line shows the expected cutoff if the cosmic ray sources were uniformly distributed in the universe. The few events above the cutoff have no explanation as to their origin in the framework of conventional astrophysics.

very interesting fact is that all such particles must undergo a surprising, although well established, phenomenon called the GZK spectral cutoff.

Shortly after the discovery of the 2.7K cosmic microwave background (CMB, the cooled down remnant of the Big-Bang radiation) by Penzias and Wilson in the sixties, Greisen and independently Zatsepin and Kuzmin predicted that at very high energies, the universe would become opaque to light or heavy nuclei. There is nothing mysterious in this: the cutoff can be observed in a laboratory experiment quite easily. When you send a photon of a few hundreds of MeV on a target proton at rest, you reach the threshold of inelastic photoproduction of pions. Now, as far as the center-of-mass energy budget is concerned (which is the only significant one) this occurs identically with the CMB photons, whose average energy is about 10^{-3} eV, in a collision with a proton of about 50 EeV. Since in each such inelastic collision, protons leave an large part of their energy (of the order of 20% on average), their energy goes below 10 EeV after a few tens of Mpc[1] whatever it was at the source. As an example, if the largest energy cosmic ray ever detected (320 EeV, i.e. more that 50 joules!) were a proton produced with an initial energy of 10 ZeV, the distance of its source should be less than 50 Mpc. One can generalize the GZK effect to heavy nuclei which lose their nucleons by spallation on the CMB photons at a quick rate. To be short, unless the UHECR are some yet unknown species of particles, they cannot come from distances larger than a few tens of Mpc. Although such distances may look enormous to pedestrians (50 Mpc are roughly 150 millions of light-years!), at cosmological scales they are more or less the size of the local super-cluster of galaxies, i.e. the suburbs of the Milky Way. This cutoff effect is visible on Fig.2 where the dotted line shows the way the energy spectrum is expected to end.

One could then say: "Well if the UHECR cannot come from large distances, then their source has to be nearby. So, where is the puzzle?" To fully understand the reason why the UHECR physics is a thrilling one, you have to take into account two more facts. The first is that the astrophysicists have the greatest difficulties in modelling cosmic accelerators able to reach the post-GZK energies. The rare models that were proposed in the past all end up in some exceptional acceleration engines. It is impossible to imagine that such remarkable engines, if in our neighbourhood, will not be visible by some exo-energetic counterparts (visible spectrum, radio waves, X-rays...). The second fact is that in the relevant energy range a proton has such a momentum that the effect of galactic or extra-galactic magnetic fields on bending its path is almost negligible: the incident direction of the UHECR should point back to its source within a few degrees. Here is the puzzle: the sources should be nearby; they are expected to be exceptional, therefore visible by some astrophysical counterpart; there is nothing visible (within a few tens of Mpc) in the direction of all the UHECR detected up to now.

Many ways were explored in order to "violate the GZK cutoff": supersymmetric (new) particles; non-standard neutrinos within the framework of recent developments based on extra-dimensions and exchange of spin-2 bosons or gravitons; violation of the Lorentz invariance of Special Relativity and so on. Of course, if true, each of these hypotheses would be a window open on a new unexplored sector of physics. However, all such models solve the problem of the propagation of the UHECR, but would explain nothing on how these have reached the extraordinary energies that we detect.

The energy puzzle: reaching the joules from below

To be accelerated at high energies, let us say 10^{21} eV (just above the highest energy cosmic ray ever detected on earth), i.e. at least several tens of joules, a cosmic ray has to be submitted to powerful electromagnetic fields. Such energies cannot be reached by any one-shot mechanism since there are no known sites where zettavolt potentials exist under stable conditions. Therefore, the acceleration mechanisms are of the same nature as the ones envisaged by the physicist Enrico Fermi in the late forties. The simplest is the stochastic and repetitive scattering by magnetic fields (second-order Fermi acceleration) where plasma clouds roughly play the role of a magnetic mirror. A particle penetrating such a cloud from the front can be scattered back, much like a tennis ball hit by a racket, with an energy larger than its initial value. However, such a process is a very slow one and to reach the energies we are interested in under normal conditions, the necessary acceleration time often exceeds the age of the universe. A more efficient and faster process is acceleration by crossing shock fronts generated in explosive phenomena (first-order Fermi mechanism) such as supernovae. However, a very simple dimensional argument shows the kind of difficulties encountered even by the most violent phenomena in the universe. We all know how a high energy accelerator works. Typically a synchrotron is a closed loop where accelerating cavities (electric fields) alternate with bending magnets. In cosmic accelerators the accelerating cavities are

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replaced by magnetic fields which vary in time therefore generating electromotive forces. However such an accelerator has to reach a natural limit in its accelerating power due to the fact that the more energetic are the particles, the larger are their Larmor radius and/or the highest are the magnetic fields necessary to confine them within the limits of the acceleration site. If the Larmor radius of the particle exceeds the size of the "accelerator" then the particle escapes from the site: it has reached its maximum energy. There is a very simple relation between those three quantities: the coherent magnetic field B needed to contain the cosmic ray within the accelerating site, the size of the accelerator R (which must be larger than the Larmor radius of the particle) and the maximum energy E_{max} that a particle can reach inside this given site: $E_{max} = ZBR$ where Ze is the charge of the particle, E is measured in EeV units, B in microgauss and R in kiloparsecs. Setting aside all technicalities, let us summarize the general consensus by saying that the product BR large enough to suit the ZeV energy range exists in no known standard astrophysical object.

Of course the imagination of the theorists knows no limit, therefore many models with extreme parameters or assumptions were proposed in the past. They mostly rely on (ultra)relativistic shock acceleration such as in hot spots of powerful radio-galaxies and gamma-ray bursts (GRB). In the first case, relativistic jets are produced perpendicular to the accretion disk around a super-massive black hole in the central part of an active galactic nucleus. The shock of the jets several hundreds of kpc from the central engine on intergalactic media is considered as being able to accelerate particles up to the highest energies. This hypothesis needs, however, to be completed by some further and necessary ingredients since such powerful galaxies are rare objects and should be clearly visible in the 50 Mpc distance authorized by propagation arguments. The second fashionable model relates the UHECR to another long-lasting astrophysical puzzle: the Gamma Ray Bursts. These are characterized by the emission of huge amounts of energies (typically a non-negligible fraction of the mass energy of our Sun) over a very short time (minutes), observed up to now as gamma rays but with, in some cases, X-ray and optical counterparts. Their distribution is cosmological and uniform over the sky. GRBs happen at a rate of 2-3 per day. However, their distribution within the "GZK sphere" does not seem to fulfill the conditions required by the UHECR observations. Other objects were proposed as putative sources of UHECR, such as rapidly rotating compact objects (young black holes, neutron stars or "magnetars") which possibly are the sources of the most intense magnetic fields in the universe (field values up to the peta-gauss have been envisaged). The capability of such systems to reach the required ZeV energies is controversial, to say the least.

▲ **Fig. 3:** Alan Watson and James Cronin, the two promoters of the Pierre Auger project. The first ideas about solving the UHECR puzzle by building a giant ground detector were envisaged during a conference in Dublin in 1991 where they met, and consolidated by an international workshop they organized in Paris in 1992. Ten years later a first piece of a future 3000 km^2 detector has started to take data in the southern hemisphere (Argentina).

The jackpot: reaching the joules from above

A simple idea is the following: since we cannot find any way of accelerating particles at ZeV energies, let us imagine that actually they are not accelerated at all, but reach the energies from above. Reaching the ultra-high cosmic ray energies from the top, i.e. as a result of the decay of a super-heavy particle is indeed quite easy, provided one can justify the existence of such particles, their survival up to the present time and the observed fluxes. If we extrapolate what we know of particle decays from the ordinary sector, a likely scenario would be the following. The mass of the particles should be typically in the Grand-Unification Theory energies ($\sim 10^{25}$ eV). They would have been created when the temperature of the universe was of the same order of magnitude, i.e. roughly 10^{-35} second after the Big-Bang. They would have survived up to now by some yet unknown mechanism (a very weakly violated quantum number, particles trapped inside huge potential wells called topological defects...). They would have accumulated by gravitational attraction in the halo of galaxies (therefore escaping the GZK cutoff). Their decay into some 10,000 secondary particles (mainly pions) by hadronization of quark-antiquark pairs would easily produce the ZeV energies we need and their decay products would then be dominated by photons (coming from the decay of neutral pions) and neutrinos (decay of charged pions). Indeed this scenario needs a series of hypotheses to work all together, but none of them calls for any extravagant model or theory. The important point is that there are a few experimental consequences of this model which constitute, if observed, a unique and irrefutable signature of the existence of the Grand Unification, a horizon toward which all the modern quantum field theories are supposed to converge. These are: a very specific energy spectrum shape extending well above the ZeV, and dominant proportions of post-GZK photons and neutrinos in the UHECR composition.

Now that we have described the contours of the puzzle, let us see how we can come out of it.

Extensive air showers and their detection

Based on very scarce observations spread over 40 years, we know that post GZK cosmic rays arrive on earth at a rate of a few per square kilometer and *per century*. On the other hand, we know that statistics are the sinew of war to solve the UHECR mystery. We need many observations to identify the incident cosmic rays, to find if their incoming directions point back to discrete sources or local mass distributions, to reconstruct precisely the shape of their energy spectrum which is, as we have seen, a specific signature of the production mechanism. The inevitable conclusion we then reach is that if we are to answer the fundamental question on the origin of the UHECR within a reasonable time, we need a detector covering a surface on earth of several thousands of square-kilometers, let's say twice the surface of Luxembourg (the State, not the Paris garden!) or one-fifth of Belgium. This was actually the conclusion reached by two physicists during a meeting in 1991, Alan A. Watson of the University of Leeds (UK), and the Nobel Prize Laureate James W. Cronin of the University of Chicago (USA) (see Fig.3). This (crazy) dream come true is the Pierre Auger Observatory, presently under construction.

Because of their very low flux, cosmic rays at the highest energies (above the PeV range) cannot be detected directly before they interact with the Earth's atmosphere (i.e. with balloon or satellite

▲ Fig. 4: One of the detector stations of the Auger Observatory in the Argentine Pampa (the Andes in the background). The complete ground array will have 1600 such stations spread over a surface of 3000 km². A typical cosmic ray induced airshower in the relevant energy range covers an area of several tens of km² with some 100 billions of secondary particles (mainly photons and electrons) that reach the ground level. The detector stations (tanks filled with 12 tons of pure water where the charged particles produce Cherenkov light) sample the shower particles, count their number and put a time tag on them. It is then possible to reconstruct the energy and direction of the primary cosmic ray. Each station is autonomous, powered by solar panels, and communicating with a central computer more or less through cellular-phone-like techniques.

borne detectors). The necessarily large-aperture detectors are therefore ground based. They must reconstruct the properties of the primary cosmic ray (nature, energy, direction) indirectly by measuring the effects of the secondary particles created by the chain reaction which results from the interaction of the cosmic ray with atmospheric atoms.

The object of the observation is what is called the *extensive air-shower* (EAS) associated with the cosmic ray. Among several observational techniques that can be used, mainly two are presently operational. The first technique is based on the detection, by a system of mirrors and phototubes, of the fluorescence light generated by the charged secondaries (mainly electrons) in the EAS. It is currently referred to as the "Fly's Eye" technique from the name of the first detector built by a team of the University of Utah in the early eighties. With such a detector, the EAS is observed in its longitudinal development and its energy is measured as in a calorimeter by the amount of UV light deposited in the atmosphere (excitation of the nitrogen molecules by the shower electrons). The second and most frequent detection technique is based on an idea first used by Pierre Auger in the late thirties. It consists of a network of particle detectors (scintillators, water Cherenkov tanks, muon calorimeters) installed on the ground. The properties of the primary cosmic ray can be deduced from the lateral distribution of the secondaries in a cross section of the EAS. The parameters of such a ground array (altitude, surface area, spacing between the detector stations) must be adapted to the energy range aimed for. The largest, presently operating ground array is called AGASA. It is situated near the town of Akeno in Japan and covers a surface of 100 km². A detector using a combination of two (or more) of these techniques (e.g. fluorescence telescopes with a ground array) is called *hybrid*. The Pierre Auger Observatory is precisely the unique hybrid cosmic ray detector.

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FIG4

The full Observatory will consist of two sites of 3000 km² each (one in each hemisphere). The ground array stations (see Fig.4) are to be distributed over the site with a regular spacing of 1.5km between each. The two sites were chosen on the basis of a list of specifications of which the most important were the size (and flatness of the landscape for easier hertzian communication), the latitude (between 35 and 40° North and South for optimum sky coverage), the altitude (around 1400 m, an altitude close to the shower maximum for a vertical shower to minimize statistical fluctuations), dry atmosphere, clear skies and low light pollution for the optical component (and partly for the solar power). The southern site is situated in Argentina, near the small town of Malargüe, Mendoza. There, a prototype detector with 40 detector stations and two fluorescence telescopes has been taking data for one year. The full detector (1600 stations and 24 telescopes) is expected to be finished in the beginning of 2005, but the data taking will go on during the construction years. We expect that with a few years of data taking with the Auger Observatory, we should have enough elements if not to solve fully the UHECR puzzle, at least to give strong indications on which paths to follow to find the right answer. But whatever the outcome, we are sure to start exploring a new domain of physics.

References

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Footnotes

(1) Mpc or Megaparsec. The "parsec" is an astronomical distance unit equivalent to 3.26 light-years or roughly 3×10^{16}m. The diameter of the Milky Way is 30 kpc, the distance to the nearest large cluster of galaxies (Virgo) is about 20 Mpc. The distance of the farthest galaxies seen, our horizon, is roughly 1 Gpc.