DESPERATELY SEEKING THE SOURCE OF ULTRA HIGH ENERGY COSMIC RAYS

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Cosmic rays

In a century which has witnessed the emergence of several completely new sciences, one would hardly expect a problem originally uncovered over 80 years ago to remain at the cutting edge of contemporary research.

The origin of the highest energy component of cosmic rays is just such a subject (one might note that superconductivity, also discovered in the first decade of the 20th century, is another). The discovery that the Earth is permanently bathed in a flux of ionizing "something" was made in 1912 by the Austrian physicist Victor Hess, who in a series of balloon ascents showed that beyond a certain height the ionization level within a sealed electroscope increases with altitude. The techniques of the time could not identify the nature of this "something"; up to the beginning of the 1930s, it was generally believed that the ionizing flux consisted of high energy gamma rays, and indeed Robert Millikan claimed that the (high) energy spectrum was crossed by "gaps", creating energy "bands" which could be interpreted as the creation energies of massive nuclei (the low energy component of the ionizing flux was clearly related to radioactivity in the Earth's surface). In the absence of any correlation with known celestial sources, high energy cosmic rays could plausibly be ascribed to an early "cosmological" period of element formation; it is just as well to recall that at that time primordial nucleosynthesis was just a dream, and Millikan's speculation was based on little more than Einstein's mass-energy equivalence principle.

In time, the ionizing "something" observed by Millikan's generation was definitely shown to be made of massive particles, essentially the stripped nuclei of the common elements, with a small admixture of electrons; as satellites became available, these particles could be observed directly rather than via the effects of their products on electroscopes, and it became clear that, apart from complications at energies below about 10^{10} eV/particle due to the perturbing effect of the solar magnetic field, the differential flux j as a function of energy E follows a power law of the type $dj/dE = E^q$, with the index $q \approx -2{\cdot}5$ (but see below).

It was in fact not until the beginning of the 1970s that γ rays were also shown to be a component of the cosmic radiation.

While satellite techniques are admirably suited up to energies of about 10^{14} eV/particle, the low flux beyond $\sim 10^{15}$ eV/particle would require implausibly large detectors or give absurdly low event rates, and a method originally suggested by Pierre Auger comes into its own.

In essence, a high energy particle impinging on the atmosphere interacts and gives rise to secondary particles, which in turn produce other secondaries, and so on. As the resultant "shower" grows in importance, the energy of each secondary decreases until various thresholds are reached. In particular, when the energy of the pion secondaries drops below a few tens of GeV, they can only disintegrate, producing on the order of 1 GeV muons which thereafter reach the ground essentially directly; electrons and gamma rays in the secondaries are however subject to various electro-magnetic scattering processes which act along the entire trajectory and so *their* energy at ground level is typically of the order of 10 MeV. Moreover, as a consequence of their different interaction histories, muons reach the ground before the secondary electrons and gamma rays.

Electrons, γ rays and muons are in principle readily distinguished from each other, for example by suitably instrumented Cerenkov detectors and scintillators, and their staggered arrival constitutes the signature of a cosmic ray event; sampling at ground level with a network of devices allows one to reconstruct the structure and composition of the shower. The total energy of the primary particle is relatively straightforward to deduce from this information, as is the direction of the primary from the inclination of the shower "wavefront"; however, to identify the primary from its final products it is necessary to compute detailed models of the shower as it propagates through the atmosphere. The problem is only a little less difficult than that of finding who owned a smashed watch some of whose fragments have been found lying in the street.

As the shower propagates through the atmosphere it excites a near ultra-violet transition of the nitrogen atom to which a dry atmosphere is relatively transparent, and so the motion of the shower front is associated with a corresponding fluorescent pulse which can be followed using a suitable photoelectric device. It turns out that the intensity of the fluorescent pulse goes through a maximum, at an altitude which depends essentially on the atmospheric structure and the nature of the primary particle. Moreover, the fluorescent intensity at its maximum is a function the energy of the primary. It is amusing to note that there is a qualitative analogy with the Chapman theory of atmospheric ionization by solar ultra-violet and X radiation.

In practise, the variation of the fluorescence with altitude, described by what is usually known as a Gaisser-Hillas function but which has a qualitative resemblance to the Chapman function, is quite complicated, and some subtlety is required to ascertain the nature of the primary cosmic ray as well as its energy from the fluorescence observations. The technique is nevertheless very powerful and when it can be exploited can identify the primary with much less ambiguity than the air shower arrays. At least two observing stations each equiped with a set of telescopes scanning as much of the sky as possible are required in order to obtain the direction of the primary unambiguously. However, the technique can only work on very clear, cloudless, dark nights, which therefore reduces considerably its efficiency as compared to the conventional giant air shower arrays. The "Fly's Eye" in Utah is at present the only exponent of this technique.

Useful summaries of cosmic ray observing methods are given by Sokolsky[13] and Sokolsky et al.[12].

Ultra high energy cosmic rays

The giant arrays and the Fly's Eye have enabled the cosmic ray spectrum to be extended to well beyond 10^{20} eV/particle – in fact, the most energetic particle so far detected (by the Fly's Eye[4] [7]) had an energy of just over 3×10^{20} eV, which corresponds, be it noted, to just over 50 joules.

A number of intriguing features emerge from all these measurements[5][6].

The energy density of cosmic rays in the region of the Earth is of the order of 1 eV/cm^3; while this is comparable to the energy density of starlight, one should keep in mind that the mean energy per particle is of course very much higher than that per photon.

From about 10^{10} eV/particle (where solar magnetic field effects become negligible) the differential spectrum seems to be a "segmented" power law, with an index $\sim -2{\cdot}7$ up to an energy of about 10^{16} eV, steepening slightly to about -3 up to on the order of 10^{19} eV, after which there is some suggestion that the spectrum becomes somewhat flatter. The spectrum is continuous at around 10^{16} eV, with no discernible discontinuity: unless one invokes some kind of *ad hoc* fine tuning, a single mechanism or two related mechanisms would appear necessary to explain the spectrum over the range $10^{10} - 10^{19}$ eV. However, the flattening of the spectrum at extreme energies is suggestive of the presence of a quite unrelated process.

Up to a few times 10^{18} eV, the cosmic ray chemical composition corresponds to the usual mix of elements, with however an overabundance of the "heavier" component. This latter effect can be understood as a simple consequence of the nuclear reactions which must occur between the "original" cosmic rays and interstellar matter; indeed, the overabundance can be used to infer the typical time cosmic rays spend wandering about before reaching us. However, beyond a few times 10^{18} eV, the chemical composition becomes "lighter"; while at present it is not possible to definitively discriminate against γ rays (but see Halzen et al.[7]) at the highest energies, it would appear that the least unlikely identification of these particles is protons (or technically, but implausibly, neutrinos). And just to add spice to the problem, the very highest energy event, that observed by the Fly's Eye, could conceivably be due to a heavy nucleus: the shower profile in this case does not provide enough information to discriminate against such a possibility.

There is some suggestion[11] that the spectrum has a gap at a little under 10^{20} eV; if confirmed, this could again imply that a new process sets in at around that energy; however, this statement should be tempered with the knowledge that only about 40 events have been observed beyond 5×10^{19} eV, and 8 events beyond 10^{20} eV.

The sources

Two generic classes of mechanism can produce high energy charged particles in the cosmos without appealing to theology. One is admirably suited to give a power law energy spectrum; the other is an excellent source of very high energy particles, but with no guarantee that their spectrum will follow a power law.

Two criteria must be satisfied for the differential spectrum to have the form of a power law. In essence, the cosmic rays have to be confined to a certain volume of space, from which they extract energy in such a way that the energy increase is a rising function of the particles' energy; a second, quite reasonable, condition, is that beyond some energy the accelerated particles leave the "active" volume.

Many years ago, Enrico Fermi showed that a charged particle "bouncing around" between moving magnetic discontinuities would gain energy from the magnetic field in just the required way. Moreover, once its energy reached a value such that its cyclotron radius is of the order of the characteristic dimension of the confining volume, the particle would necessarily tend to leave.

The simplest way to apply Fermi's theory is to assume energy equipartition between the magnetic field and the randomly moving plasma in which it is embedded, and to farther assume that sufficient time is available for the cosmic ray particles to reach energy equipartition with the moving magnetic "mirrors". Assuming finally that the only way energy is lost from this system is via the evasion of sufficiently energetic particles on a time scale longer than that to reach equipartition, it can be shown very easily[9] that the equilibrium differential spectrum is a power law in energy, with an index exactly equal to $-2{\cdot}5$.

The good news is thus that the observed cosmic ray spectrum could be a simple consequence of a rather general process.

Now for the bad news: close as this result is to observation, it disagrees with it in a fundamental way. As noted in the introduction, the spectrum has at least three different power law indices depending on the energy range. Presumably perfect energy equipartition is not a feature of the acceleration process, and it becomes necessary to compute detailed models.

These are parametrised essentially in terms of two quantities:

1. the time scale t_a for the acceleration by the Fermi "bouncing" mechanism, and
2. the time scale t_l to leave the accelerating region, for example by some kind of diffusion process.

In such a case, it can be shown (but not so easily[9]) that the resultant power law spectral index is equal to $-(1 + t_a/t_l)$.

Clearly, different models of the accelerating region lead to different values of the index, and it becomes possible to "fine tune" the result of most models to the observed values... although it must be said that the simplest models of this type lead to power law indices very much farther from observation than the extraordinarily simple, but somewhat miraculous, equipartition theory (this is presumably what miracles are all about!).

Typical configurations which will accelerate particles in this way include[3] the magnetic field of the Sun, the turbulent interstellar medium, shock waves produced by supernova explosions, shock waves produced by relativistically moving compact objects through the interstellar or intergalactic medium, the shocks associated with the motion of galaxies or galaxy clusters through the intergalactic medium, the jets and their endpoints ("lobes" in the jargon of the radio astronomer) associated with certain radio galaxies, and various combinations of such structures.

However, whatever the details of the accelerating process, we know that it can only work if the particle remains trapped in the accelerating region, and it can only remain trapped if its Larmor radius is smaller than the characteristic dimension R of the volume. Therefore, the energy T of a particle of charge Ze is limited by:

$$T \quad < \quad ZeBR \tag{1}$$

where B is the characteristic large scale magnetic field responsible for trapping the particles in the accelerating region.

A totally unrelated mechanism relies on the ability of a suitably constructed homopolar dynamo to produce an intense electric field. Suppose[9] that over some distance scale R a magnetic field B is moving with speed v_B. The induced electric field due to the motion is of the order of $v_B B/c$, and so the energy that a particle of charge Ze can reach is limited by:

$$T \quad < \quad ZeBR\frac{v_B}{c} \tag{2}$$

Clearly, the higher the field and the higher the velocity the better; typical dynamos might be the magnetospheres of neutron stars where magnetic fields could reach on the order of 10^{12} G and the velocities would be relativistic, thereby compensating easily for the small dimensions, and the central engines of active galaxies where it is believed that billion solar mass black holes could be accreting matter and magnetic fields from the surrounding galaxy.

However, while the performance of these "dynamo" accelerators is limited by the magnetic field available (in the first instance, but see later), we know of no natural way for them to generate a power law spectrum. The significance of this depends on one's point of view; we know that the bremmstrahlung radiation of material in the immediate vicinity of pulsars (the "visible" neutron stars) does have a power law spectrum, which can be interpreted as signifying that the pulsars have some way of producing particles with a power law spectrum, even if we do not at present know how.

We do not know *a priori* whether the observed cosmic rays are of galactic origin or not. However, we can impose a distance limit on the source of the highest energy cosmic rays, since the ubiquitous 3 K fossil radiation degrades the energy of particles which pass through it. In effect[9], in the rest frame of, say, a proton with Lorentz factor γ, a photon of the background radiation has energy of the order of $6 \times 10^{-4}\gamma$, and significant pion production can occur if this exceeds 200 MeV. In other words, if the proton energy exceeds about 5×10^{19} eV, it will lose a large part of its energy; the cross-section for this process is known, and leads to the conclusion that no protons with energies significantly in excess of 7×10^{19} can reach us from beyond a few tens of Mpc. This is known as the Greisen-Zatsepin-Kuzmin cutoff: if indeed the ultra high energy cosmic ray component is made of protons, and their source region is beyond this critical distance, the spectrum should stop at $\sim 7 \times 10^{19}$ eV, or should have a gap, the more energetic protons then being produced relatively close by.

The background radiation has yet another effect whose significance in this context is however difficult to assess: ultra energetic heavy nuclei passing through the fossil radiation will be gradually "stripped" down by photodissociation, losing about four nucleons per Mpc. Consequently, a 10^{20} eV proton arriving here could conceivably be the remnant of, say, an iron nucleus which started on its jurney about 50 Mpc away. This phenomenon does increase the volume for potential sources (which nevertheless corresponds, cosmically speaking, to our galactic suburbs); it also suggests that we should not be able to observe heavy nuclei at these energies from such sources. And one would expect this effect to smooth out the Greisen-Zatsepin-Kuzmin cutoff: the detailed topography of the energy spectrum around 10^{20} eV thus carries critical information about the type of process responsible for the ultra high energy particles observed.

Note that analogous effects will operate in compact regions of very high temperature and high photon density – high energy particles will have difficulty leaving such regions "intact".

Finally, γ rays and (of course) neutrinos can reach us from considerable distances – for a proper understanding of the observations, it is vital to eliminate these latter as candidates for the highest energy component.

Equations 1 and 2 are direct functions of the nuclear charge Ze. With a given "technique" it is clearly "easier" to accelerate heavy nuclei to a particular energy than protons – we see in this way the importance of identifying the primary cosmic ray.

These two equations have of course a functional similarity, which allows one to study the "performance" of the different possibilities in a unified way, by seeing whether the associated magnetic fields, sizes and velocities are capable of creating the highest energy cosmic rays.

It emerges immediately (see Hillas[8] for a very clear summary diagram) that supernova remnant shock waves, turbulent motions within our galaxy, etc. cannot produce protons more energetic than about 10^{16} eV; on the other hand, with a slightly more subtle analysis, it turns out that the energy density of cosmic rays requires only a small fraction of the mechanical energy of supernovae in our galaxy. These latter can thus explain the overall energy budget of cosmic rays, but not the higher energy component. For this, it is necessary to invoke either the shock wave produced by a (hypothetical) outflow of material from our galaxy (such outflows are observed in other galaxies), or the dynamo acceleration of particles by the neutron stars left over from the supernova explosions. The former process would be in fact boosting the lower energy particles to higher energies: consequently, spectral continuity would be maintained right up to the maximum energy that this process can produce, which is nevertheless limited to on the order of 10^{19} eV. The neutron stars could conceivably accelerate particles as far as 10^{20} eV, and since they are the products of the supernovae whose remnants would be responsible for the lower energy cosmic rays, one might intuitively expect some kind of spectral continuity; however, we do not know why the spectrum should be power law, and so for the time being this must be considered an *ad hoc* hypothesis. Furthermore, attractive as neutron stars seem to be as sources of the highest energy cosmic rays, they do suffer from a fundamental defect: the very property which makes them such good candidates – their intense magnetic field – eliminates them, since the accelerated particles will of necessity have to first pass through this very same field, and therefore lose a substantial fraction of their energy through curvature radiation.

The "central engines" of active galaxies are expected to have sizes and magnetic fields capable of accelerating protons to about 10^{20} eV (the expectation emerges essentially from a consideration of the energy available in such objects: the actual processes responsible for the energy conversion, and their efficiency, are far from clear). However, the highest energy protons we are observing (if such they are) cannot come directly from these galactic power houses: we know that the nuclei of active galaxies are sources of intense and high temperature radiation, so that the highest energy cosmic rays will lose most of their energy before leaving the source region as a consequence of photopion production (through essentially the same process as produces the Greisen-Zatsepin-Kuzmin cutoff on the cosmological scale). Of course, there is no reason why the nuclei of active galaxies should accelerate only protons, since the material accreted onto the central black hole must surely contain all the elements: it is not inconceivable that photodissociation by the radiation field around the black hole and by the fossil radiation along the trajectory to us, could leave as a remnant the very high energy protons... but then there should definitely be no ultra-energetic heavy elements. And some remarkably fine tuning is required to strip away just the supernumerary nucleons without also degrading the energy of the surviving proton.

We see again the importance of identifying unambiguously the nature of the primary cosmic rays at the highest energies. Moreover, only sources within 30-50 Mpc could contribute significantly through this process.

Rich and compact galactic clusters could accelerate protons to the requisite energies (but this is an affirmation of dubious significance, since at present we only have upper limits on the value of the intergalactic magnetic field), again via shock waves of some kind produced by the individual galaxies. However, we now know that the intergalactic material in such structures is rich in heavy elements – their highest energy products can be exclusively protons only through a process of photodissociation.

Photodissociation of the heavy nuclei will certainly aleviate the problem of their apparent absence at ultra high energies (remembering, however, that the Fly's Eye superevent might have been an iron nucleus)... but at a price. In essence, each nucleon which is knocked off by the cosmological photons carries away its share of the nucleus' energy, so that the total initial energy of, for example, an iron nucleus of which a 10^{20} eV proton survives at Earth, must have been at least $5{\cdot}6 \times 10^{21}$ eV. Now, equations 1 and 2 do suggest that with a given accelerator there might be no fundamental difference between accelerating a proton to a given energy and accelerating a nucleus of charge Z to Z times that energy; however, the number of nucleons in heavy nuclei, and so the required initial energy for a given final proton energy, grows twice as fast as the nuclear charge. Whilst a factor of two may seem like a niggling detail compared to the order of magnitude which separates reality from plausible and calculable theory, one would surely have felt more comfortable had the factor been one half.

Shock waves in the intercluster medium (which is presumably less contaminated by the products of stellar evolution) cannot be eliminated *a priori* as sources for the highest energy cosmic rays even if these are only protons, although one might note that we know even less about the value of magnetic fields on this very large scale than on the intergalactic scale. However, the scale at which this mechanism must operate if it is to produce 10^{20} eV protons with the aid of fields which do not exceed the known upper limits, runs into the hundreds of Mpc range: consequently, even if $> 10^{20}$ eV protons are produced in this way, we will not see them at these energies because of the Greisen-Zatsepin-Kuzmin cutoff.

In fact, the only structures potentially capable of producing $\geq 10^{20}$ eV protons but which have no evident defects of a rather general nature are the jets and shocks ("lobes") associated with certain radio-galaxies.

Desperately seeking

Within 50 Mpc of our galaxy are a handful of galaxy clusters known as the "Local Group". This region also contains a number of powerful radio-galaxies.

A search[14][10][13] for some correlation of the arrival directions of cosmic rays with suitable structures in the sky has led to the following conclusions.

The distribution is perfectly isotropic up to an energy of about 10^{18} eV. This is to be expected whatever the source region might be: below this energy, the Larmor radius of particles in the magnetic field of the Galaxy is a small fraction of its size, and so the cosmic ray has little chance of preserving any memory of its original direction.

Between about 10^{18} and a few times 10^{19} eV, the distribution is reasonably well correlated with the plane of the Galaxy. This suggests that these particles, and so by extension the lower energy particles, originate from sources associated with our galaxy.

However, the highest energy cosmic rays, up to about 10^{20} eV, seem to be correlated with a plane perpendicular to that of our galaxy. Now, the "Local Group" of galaxies forms a vaguely flattened structure whose plane is in fact perpendicular to the Galaxy, and in which it turns out that many radio-galaxies are to be found. One would be tempted to invoke a "Local Group" origin for these highest energy cosmic rays, were it not for the fact that no specific cases of coincidence have ever been detected. While this is undoubtedly not surprising for cosmic rays whose energy is less than 10^{20} eV, since over tens of Mpc such particles will be deviated significantly from their original directions by the intergalactic magnetic fields (of whose value we only know the upper limit), it is at the very least disturbing for particles well beyond 10^{20} eV: the three highest energy cosmic rays known to date, whose deviations from their original direction cannot exceed ten degrees, come vaguely from the galactic anti-centre direction but have no relation to any known energetic source or galaxy cluster in the local group, and the objects closest to them on the sky are actually at distances which range from 60 to 1000 Mpc, i.e. well beyond the Greisen-Zatsepin-Kuzmin cutoff[10].

Could these ultra high energy cosmic rays be from a completely new type of source, within the Local Group (Greisen–Zatsepin-Kuzmin *oblige*), but in no way related to known galaxies or other structures? Could these particles in fact have been created with such high energies, thereby obviating the need for powerful cosmic accelerators? It is tempting to claim the apparent (but statistically debatable) gap in the differential spectrum below 10^{20} and the possible spectral flattening as indications that something like this is in fact happening[11][10]; massive, but speculative, decaying topological defects which are a possible product of the phase changes which might have followed the Big Bang and which could perhaps have survived to the present epoch have been invoked, as have primordial strings (no less speculative) actually interacting with the Earth's atmosphere... but in the present state of the art there is really nothing very compelling about these *avant garde* theories.

And in the absence of any better idea, there is even some speculation that the source of these particles could be in some way related to γ ray bursters: the feature they share is that we understand neither the one, nor the other.

The shade of Millikan looks on with deep interest and a certain wry smile: his dilemma is still ours, simply moved upwards in energy by a factor of at least 10^{14}, and just as he saw "bands" in the spectrum, we may (or may not) be seeing a "gap" in the high energy spectrum.

Opening a new astrophysical window

The study of ultra high energy cosmic rays is clearly severely constrained by statistics. In the region of 10^{20} eV the particle flux is of order 10^{-2} events/year/km^2. If the energy spectrum is a continuation of that at lower energies, this event rate drops by two orders of magnitude at 10^{21} eV. With such low fluxes, the essential task of mapping the shape of the high energy spectrum poses a considerable challenge. Moreover, there is at present no operating shower array of any sort in the Southern hemisphere, while even in the Northern hemisphere the sky coverage is very incomplete. This is particularly unfortunate, since the galactic centre can only be observed from the Southern hemisphere, so that the apparent correlations with the anti-centre direction or the supergalactic plane, already statistically weak, could even very easily be a pure artefact. Note too that the recently discovered galactic superluminal sources, which are presumably local, miniaturised, versions of active galactic nuclei and might well be capable of accelerating protons to extreme energies, are all towards the galactic centre.

The "Auger Cosmic Ray Observatory[1]" will be an attempt to improve the observational situation by orders of magnitude.

At the present time, the largest working air shower detector (called AGASA) is in Japan, and consists of about a hundred 2 m^2 scintillators spread over an area of roughly 100 km^2. The only fluorescence detector is the Fly's Eye, in the U.S.A., which consists of two "all sky" photomultiplier stations separated by 3 km; one station has about 900 photomultipliers, and the other a little under 500.

The "Auger Cosmic Ray Observatory" will consist of two "hybrid" detectors, one in the Northern and the other in the Southern hemisphere. Each will:

- have about 1600 water Cerenkov detectors spread over roughly 3000 km^2, with a 1·5 km spacing;
- be associated with two or three (depending on details of the terrain) "fly's eye" type of fluorescence detectors, which will scan the sky with about 50 mirrors and 200 pixels per mirror.

The system is being designed for an operating lifetime of at least twenty years, with minimal maintenance and maximal autonomy. This raises a number of problems, whose solution is being actively sought; two examples suffice to show the nature of the difficulties:

1. the Cerenkov counters must be associated with very fast electronics capable of recognizing short pulses with good discrimination; the electronics must operate on low power and be very reliable;

2. sophisticated triggering techniques are required to avoid contaminating the data with noise; this entails extremely accurate synchronization of the Cerenkovs, and intercommunication between them. The results of a successful trigger will of course have to be communicated to a central station. Since the arrays will be in remote desert locations, and will involve very many detectors, it is quite unrealistic to envisage cable links: radio telemetry will be the watchword.

If all goes well, the system should begin operating in about the year 2000. It is estimated that after ten years in action, the full Auger array should have of order 1000 events above 7×10^{19} eV "in the bag", of which about 500 should be above 10^{20} eV and 5 above 10^{21} eV *if the spectrum continues* with the same gradient as before. Note that up to about 10% of these events will also have been observed by the Fly's Eye detectors.

While there is no guarantee that such an improvement in statistics will necessarily solve the conundrum of the ultra high energy cosmic rays, it is certain that in its absence the field is limited to the wildest speculation.

Contemporary astrophysics is faced by a number of acute problems.

One of them concerns dark matter, which one might (perhaps mischievously) qualify as the study of particles which *should* exist... but until farther notice, don't.

Ultra high energy cosmic rays constitute the inverse problem: particles which *do* exist... but perhaps shouldn't.

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CHERCHE SOURCE DES RAYONS COSMIQUES ULTRA-ENERGETIQUES... DESESPEREMENT

Depuis quelques années, nous savons que le spectre du rayonnement cosmique s'étend endeça de 10^{20} eV, et nous avons des fortes présomptions qu'il s'agit de protons. Ces particules ne sont associées avec aucune source céleste connue; d'ailleurs, on ne sait pas par quel processus des protons peuvent être accélérés à de telles énergies. Le projet "Auger" vise à mettre l'étude de ce nouveau fenêtre astrophysique sur des bases solides.