The origin of cosmic rays to 10^{21} eV

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Abstract

To probe the innermost structure of matter we build extremely large accelerators, such as in CERN, Fermilab, or Stanford. Nature provides us with particles at much higher energy - the cosmic rays. Cosmic rays are mostly protons, electrons, nuclei of different chemical elements, photons, anti-particles, and quite possibly particles which we cannot identify yet. We have observed energetic neutrinos with the AMANDA detector, and hope to detect despite considerable uncertainty, particles of a very different nature, such as monopoles, and supersymmetric particles. The highest energy of a single particle observed to date - detected with the Fly's Eye detector in Utah, USA - is of macroscopic energy. We still do not know for certain where cosmic ray particles come from. Supernova explosions are the best proposal for the cosmic ray energies from GeV, possibly to $\sim 10^{18}$ eV, and they may so account for most of the energy range observed. Ironically, the detectors at CERN (and, presumably, at other high energy laboratories) detect the products of cosmic ray interactions directly, and provide unique data to test their properties near and beyond 10^{15} eV, thus providing additional information on the energy range where the Galactic origin is likely, but not certain. At the highest energies the particles must come from outside our own Galaxy. What could the nature of these particles be? Where do these particles come from? By now the most conservative proposal to survive all tests is the notion that powerful radiogalaxies accelerate these particles as protons in their large hot spots, but if so, which radio galaxy? However, we lack certainty already from below 10^{14} eV as to their origin, and so the cosmic ray particles and their interactions offer the chance to do physics from below 10^{14} eV to 10^{21} eV.

1 Introduction - History

Cosmic rays have been a riddle since their discovery [44, 50]. Now, with energies going far above anything available in experiments, the challenge has intensified.

Here we briefly summarize some of the arguments on the origin of cosmic rays from below 10^{14} eV all the way to the maximum observed, near 10^{21} eV.

After giving some introductory concepts, we will review the various physical concepts as to get particles at these extreme energies, then we will discuss the data and possible source theories, and finally end on some speculation and give an outlook to the future.

We restrict the reference list to recent literature, and ask the reader to consult the review articles mentioned. There are several books on the subject [4, 36, 52, 91, 66, 69], and for reference I also list here review articles [16, 17, 26, 38, 45, 104, 12]. Of the older literature, only some of the more classical papers are mentioned. Recent reviews on high energy cosmic rays are [17, 12]. The literature list given below contains entries, not mentioned in the text for lack of space, but relevant to the topic.

2 Extragalactic cosmic rays

Graphs No. 1 - 15. These graphs are to ge found on the CosmoLep homepage at CERN, under "conference".

As the Larmor motion in the Galactic magnetic field cannot contain any proton, the most common particle in cosmic rays, as far as we know, above about $3\,10^{18}$ eV; therefore, we expect that from this energy the events we observe originate outside our Galaxy, presumably far outside. This argument was made in 1956 by Cocconi already [24].

Fittingly, there is a kink in the overall spectrum near $3\,10^{18}$ eV; the spectrum becomes slightly flatter, from about $E^{-3.1}$ to about $E^{-2.7}$. At such an energy, protons already have suffered from interaction with the microwave background, and so any injection spectrum is severely flattened. Also, there are now a variety of independent analyses which demonstrate that the chemical composition at that energy changes from heavy to light; that is, the chemical composition also shows a clear transition at that energy. Taken together, this suggests that a flatter source spectrum overtakes the steeper Galactic cosmic ray spectrum from below, and dominates from there on out.

The interaction with the microwave background should produce a cutoff near $5\,10^{19}$ eV, the GZK-cutoff.

The new AGASA data (Takeda et al., 1999 [95]) show that the spectrum continues to well beyond the GZK-cutoff. The maximum energy of any event comes from the Fly's Eye array, and is $3\,10^{20}$ eV. The number of events beyond 10^{20} eV, a factor of 2 beyond the GZK-cutoff, is in the new AGASA data alone 7, and beyond $6\,10^{19}$ eV it is 17. The world set is over 14 now with energies above 10^{20} eV, albeit with different energy error bars; this uses a list of Watson [104].

Such maximum energies are a serious problem, e.g. [7], because for a cosmologically homogeneous distribution of powerful astronomical sources, that individually emit protons at any energy, even to 10^{24} eV, the GZK-bound should be observed. On the other hand, with a different type of source, smoothly distributed in space, such as could be caused by the decay of Big Bang relic particles, the GZK-cutoff could be seemingly avoided; there would be enough local, invisible sources, which contribute.

One interesting finding is that the arrival directions appear to cluster [84, 66], that is several events at different energies each seem to come from the same spot on the sky. This can be explained in two ways: 1) The arrival directions are just more likely to come from some extended region, like the supergalactic plane, and then the likelihood that some events appear to cluster along the plane, is high; but in this case the different events that appear to cluster do not relate to any particular single source. 2) Obviously, the opposite may be true, and then these events may come from a specific source, whatever that source may be. But, as shown by Cronin (Tokyo meeting, [66]), then the charge of the individual events can be limited, since a particle of higher charge would be much more bent in its path than a particle of a single charge, and hence it is likely that all these particles have the same charge.

A further possibility is that such events correlate with particular astronomical objects on the sky. Some events seem to come from close to the active galaxy M87, others seem to relate to distant quasars: The arrival direction of the Fly's Eye event at $3\,10^{20}$ eV sits close on the sky to several active radio galaxies, such as 3C134 and 3C147, while the most energetic AGASA event is close a PG quasar [16], and also close to several compact radio galaxies, as pointed out by Farrar & Biermann [31]. The challenge with these suggestions is that the distance to some of the proposed sources excludes protons as the possibly particles that come here.

2.1 Physical concepts

The basic physical concepts to explain very high energy particles start from the same as for Galactic cosmic rays [2], and thus from Fermi acceleration.

Intergalactic magnetic fields are there, and have a variety of strengths [49, 96, 53]. Outside the Coma cluster there is evidence [49] from extended synchrotron emission, that there magnetic fields have about 10^{-7} Gauss.

The key point is that extragalactic magnetic fields are just as clustered as galaxies are, and show the analoguous large variety of strengths.

Protons and neutrons both have strong interaction with the microwave background, losing about 20 % of their energy every time they interact. The mean free path to individual collisions is of order only 10 Mpc, and so shorter than the distance to the Virgo cluster. This leads to a cutoff in the expected spectrum, provided the sources are distributed cosmologically in a homogeneous fashion, and have a reasonable lower limit to their distance to us, the GZK-cutoff, at $5\,10^{19}$ eV.

Other particles, given sufficient energy, will also interact, then with the Big Bang neutrino background, with the microwave background, and the background in the radio through shorter wavelengths from galaxies [70], and active galactic nuclei. This can lead to considerable cascading, nuclear spallation and degrading of the particle energy [92, 93].

3 Models and tests

Graphs 16 - 42.

There are now 14 events clearly claimed to have an energy above 10^{20} eV, and there are quite a few theories. We will discuss them in turn, and try at each instance to give a critical appraisal of the proposal.

3.1 Gamma Ray Bursts

Since 1997 Gamma Ray Bursts (GRBs) have been identified with afterglows in the optical, X-rays, and radio wavelengths [52, 69]. This progress was made possible by the Italian-Dutch satellite BeppoSax. GRBs come from cosmological redshifts, have a fluence of up to $\sim\ 10^{-3}$ erg/cm^2, peak in their photon energy somewhere in the 100 keV to MeV range, and last from fractions of a second to a few hundred seconds. In one case there was late emission in GeV photons after about one hour. With the assumption of isotropy of the emitted radiation the maximum total energy works out in some cases to more than the rest mass energy of a solar mass star, especially considering the GRBs 990123 and 971214.

Even if the energy is not isotropic, it is clear that gigantic energies are indeed involved, with the lowest estimates still of supernova scale, e.g. [72]. Almost all models use a highly relativistic explosion, that would naturally produce high energy particles, such as protons, neutrons, photons and neutrinos

[99, 100, 97, 76, 77, 78] . A tell tale sign would be a temporal and spatial correlation between a GRB and the arrival of an energetic neutrino.

3.2 Relic decay

Relic decay has many advantages [83, 10, 11, 8, 9]. This proposal has the advantage that it naturally gives 10^{24} eV protons, but a large part of the energy goes into photons and neutrinos, which cascade, and may or may not overproduce the gamma-ray background. Future Gamma Ray satelites and ground based Čerenkov telescopes will shed light on this.

As one kind of the possible relic particles monopoles are expected resulting from the Big Bang. They either short-circuit magnetic fields, given sufficient flux, or they get accelerated in existing magnetic fields [48]. In work with Weiler & Kephart (as yet unpublished) we have shown that the cosmic magnetic fields naturally lead to monopole energies above 10^{21} eV, quite possibly even to 10^{24} eV. However, there seems to be no way yet to convincingly argue that monopoles at such energies also produce air showers that look like proton-induced showers of an energy near 10^{21} eV [27].

3.3 Active Galactic Nuclei

The best tested concept is that the outer radio lobes and their hot spots of powerful radio galaxies produce in their shock waves the high energy cosmic ray particles [13]. There, the maximum energy that can be produced depends on the power of the source, and the magnetic field strength, and so, going to the most extreme sources known, and adding some factor for possible relativistic boosting, we may reach 10^{22} eV, but only for rare sources, that are far away. Nearby sources which are candidates to reach close to 10^{21} eV, are the radio galaxies M87, NGC315, and possibly 3C134 [16, 17]. Given, that magnetic fields can bend the paths of such particles, if charged, e.g. [56], this may be all that is needed. The graininess of the spatial distribution of these few candidate sources may explain the apparent lack of a GZK-cutoff should really be there.

One specific model using active galactic nuclei is the concept, that a relativisitic compact jet accelerates protons to very high energy, and then a few of these protons are converted to supersymmetric particles in a beam dump [31]. There is an attractive class of radio quasars, that may be interpreted as such, the radio sources referred to as GPS (Giga-Hertz-Peaked sources) or CSS (Compact Steep Spectrum Sources) [67]. A spatial correlation in arrival direction with radio quasars of this class would strongly hint at such a possibility, which would allow the particles to reach us from high redshift.

4 Bridging the gap: Where do cosmic rays above 10^{14} eV come from?

Graphs 43 - 55.

Sofar we have argued about the cosmic ray particles from a few 10^{18} eV, up to 10^{21} eV. However, there is little certainty even at much lower energy. We will need to understand these energies, because they provide the bridge between accelerator energies and the highest energies observed.

Fermi acceleration in shockwaves of supernova remnants in the interstellar medium has been the classical and well tested theory, and many theoretical arguments tend to confirm that they do provide particle energies to about 10^{14} eV (work by Axford and collaborators, Lagage & Cesarsky, Völk and collaborators, Ellison, Drury, Ramaty and others, see [104]). However, this energy does not even reach the knee feature at about 5 10^{15} eV, where the overall spectrum turns down.

So, where do these energies come from? What is the chemical composition of these particles? There have been several arguments in the literature:

- First of all, it has been supposed for some time, that the turn down at the knee is due to a propagation effect. However, there is no scale in the interstellar medium that would do this.
- Second, there has been the suggestion (Axford expecially), that distributed second order Fermi acceleration could extend the particles energies all the way to near 10^{18} eV. However, this argument is not quantitative; no prediction has been made, that could test this concept. Also, there is a question whether such a process is sufficiently fast, to both give a well defined powerlaw, and full isotropy.
- Finally, there is the proposal (Biermann), that the knee is due to a diminished efficiency of acceleration in a SN-shock running through a magnetic stellar wind. The process of acceleration is also Fermi-acceleration, just in a very different environment, with a much faster shock, and a much more magnetic medium, a magnetic stellar wind. This last suggestion is quantitative, and some of its predictions have been tested.

The predictions of this last picture are as follows: The spectra of all chemical elements in the cosmic rays are the same (except for the effect of spallation) from Helium all the way to Iron, with a slope of near -2.67 below the knee, and near -3.07 above the knee, and the knee itself is near 700 Z TeV, where Z is the charge of the particle under consideration. The theoretical uncertainties in the spectral indices are of order 0.03 and 0.07, respectively, and in the rigidity of the knee probably more like a factor of 2. The source is argued to be massive stars, which explode into their own stellar wind, which is highly enriched due to heavy mass loss. These predictions have been successfully tested with the earlier AGASA data [87]. The normally considered supernova explosions into the interstellar medium provide only energies up to near 100 TeV, have a spectrum near $E^{-2.75}$, and so Hydrogen is turning off before the knee. The knee should then be visible mostly in Helium through Iron, an energy range of a factor of about 10. The chemical abundances should then reflect the numbers of massive stars on the zero-age-main-sequence, with the normal supernovae, exploding into the interstellar medium, the most frequent but local abundances, those stars with strong winds and moderate enrichment next in frequency, with mostly Helium enrichment, and the most massive stars with extreme enrichment the least frequent, but the dominant source population in cosmic rays for the heavy elements such as Carbon and Oxygen. This latter proposal remains to be tested in detail.

The specific prediction in 1993 [15] had been that the spectrum below the knee is $E^{-2.67-0.02\pm0.02}$, and above the knee of $E^{-3.07-0.07\pm0.07}$. The theoretical error distribution had been expected to be asymmetric, with the most probable spectral slope being -2.67 and 3.07, respectively.

What is a special challenge to understand, is the relative sharpness of the knee. Just the phase space mixing in pitch angle (the angle between the local prevailing magnetic field and the path of an energetic charged particle) should give a smearing of the knee of about a factor of at least 2; this is in addition to the smearing introduced by the various "knees" of the different elements, which already is a factor of at least 10. The requirement that many sites contribute to the build up of the cosmic ray flux at the knee implies, that whatever those sites are, they must be very similar. The underlying rigidity of the knee must relate to magnetic fields, and their scales. Within the concept proposed above this means that the magnetic field in very massive stars must relate to the explosive energy (see paper [14]) rather directly, and this connection ought to be very nearly identical for all very massive stars.

It is important to realize, that the knee is smooth allowing for both the various elements and their specific "knees", and the isotropy in the pitch angle distribution. In addition there must be a distribution of source properties, which still adds to a further smearing of the knee. What is astounding, is that this distribution of sources “knee rigidities” is not large, but apparently quite limited.

Independent of any particular theory, the concept to be tested is then as follows (inspired by the work of B. Peters in the late 1050ies, and early 1960ies): Take the airshower data of the different experiments and ask:

- What is the spectrum below the knee? Which elements dominate there? Do we have a good transition from the JACEE data?
- At lower energy do we explain successfully the abundance of positrons and anti-protons and their spectra? The gamma ray emission spectrum from the inner Galaxy, as well as the spectra of secondary nuclei?
- What is the spectrum above the knee? Which elements dominate here?
- What is the underlying rigidity of the knee?
- What underlying sharpness/smoothness of the knee is required, if any?
- Do we get a good transition towards the ankle in spectrum, flux, and chemical composition?

It is interesting to notice, that the CASA-MIA results [39, 40] nicely confirm the 1993 predictions and early checks [87, 15], with a spectrum of $E^{-2.66\pm0.02}$ below the knee, and $E^{-3.00\pm0.05}$ above the knee, and a smooth range of “knee”-energies likely corresponding to the various elements turning over in sequence of their nucleus charge. This is also in agreement with the EAS-TOP determination [1] of a spectrum of $E^{-3.19\pm0.06}$. CASA-MIA also confirms the trend to a composition that becomes heavier.

It will be a serious challenge to ask these questions with the new and further data sets (and further, even more careful analysis) from CASA-MIA, DICE, GRAPES, HEGRA, the TIBET array, (see paper CR VII, and [1, 23, 39, 47, 104]) and so to determine whether this simple analytical theory can be confirmed or definitively rebutted.

5 Conclusions

Graphs 56 - 58.

We have considerable difficulty discussing the physics of the particles above 10^{18} eV, as long as we cannot be certain of the origin and nature of the particles above 10^{14} eV. Here any new dataset, such as possible from the large CERN experiments, is precious, and highly welcome.

The future will bring new experiments, and new observations. Which will be most interesting to watch for?

- Is the knee at $5\,10^{15}$ eV smooth in its properties, and does it signal the switch to another source population?
- What is the chemical composition of the cosmic rays across the knee? Are there several “knees”, one for each element?
- Is there a special component of cosmic rays, just peaking up near knee energies, but otherwise undetectable?
- Is the switch in chemical composition from heavy to light near the ankle, at $3\,10^{18}$ eV, confirmed? And some wonder, is there any further switch, possibly back to heavy at the top energy?
- Is there any spectral feature near the expected GZK-cutoff energy, at $5\,10^{19}$ eV?
- What is the real maximum energy?

- Do the arrival directions on the sky correlate with any specific objects?
- Is the timing of events coincident or close to the timing of any other celestial event, such as Gamma Ray Bursts? Is it coincident or close in time to neutrino events in the AMANDA neutrino experiment at the South Pole?
- And last, but most importantly, what is the real nature of the particles at the top end in the energy range observed?

It is clearly still possible to devise models for powerful radio galaxies, their cosmic ray acceleration and the intergalactic magnetic field, that satisfy all known constraints and explain all events observed. After all, the energy of 10^{21} eV was derived in 1987 already [13], before the really high energies were discovered, using the active galaxy M87 as an example, with a distance of order 20 Mpc. On the other hand, the data bring us to a rather unsatisfactory point, where we need to stretch all the models available, and push further than we anticipated, when we made the various predictions.

Cosmic ray particles at all energies up to 10^{21} eV offer us one of the greatest challenges in astrophysics and particle physics, and the next ten years can be expected to bring decisive progress, with cosmic ray air shower arrays, and with high energy neutrino experiments.

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