

# The Cosmic-ray Spectrum: from the knee to the ankle

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**Abstract.** This talk addresses the question, “Where is the transition from cosmic rays of galactic origin to extra-galactic cosmic-rays?” I have addressed the background of this topic recently in lectures at Erice [?] and, with Todor Stanev, in a collection of papers on various aspects of nuclear astrophysics [?]. Here I concentrate on primary composition as a signature of the transition and mention some new air-shower experiments aimed at the energy region from the knee to the ankle (PeV to 10 EeV).

## 1. Introduction: Lessons from lower energy

It is a commonplace, nearly a century after the discovery of cosmic rays, that their origin remains a mystery. Statements to this effect can often be found in the introductions of review papers and in proposals requesting funds for new experiments.

I would argue that this claim is wrong. In fact, we know a great deal about the nature of the sources of cosmic rays, about the source of power for their acceleration, and about the acceleration mechanism itself. Moreover, what we know about cosmic rays in the GeV to TeV range and how we know it gives useful guidance for how to extend our understanding to the PeV to EeV range and beyond.

From detailed measurements of the relative amounts of different nuclei and isotopes, it is possible to infer the abundances required at the sources. To do so requires accounting for changes in abundances of different nuclei as they propagate for several million years through the interstellar medium [?, ?]. It is also necessary to account for the relative ease of accelerating different kinds of nuclei. In particular, refractory elements initially remain attached to dust grains, which are more efficiently injected into the acceleration process than individual ions. So refractory elements are enhanced in the cosmic radiation [?]. Putting the propagation effects all together, there is strong evidence now that a class of supernova explosions involving the rapid evolution and collapse of massive progenitor stars (Wolf-Rayet stars) provides a significant fraction of the observed cosmic rays, as explained in the talk of Bob Binns at this conference [?].

It has been known since the 60s that supernova explosions produce just the right amount of power to generate the observed cosmic radiation if about 10% of the kinetic energy goes into accelerating cosmic-rays to high energy. This observation is largely the contribution of Ginzburg and collaborators [?]. The result is obtained by integrating the energy density of cosmic-rays in the interstellar medium and taking account of the energy-dependent propagation time of cosmic rays before they escape the galaxy [?, ?]. As shown by Ptuskin at this conference, the numerical result is robust and independent of details of the propagation models [?].

The acceleration mechanism itself is most likely the result of shocks driven by supernovae exploding into the debris of stellar winds from the progenitors before they collapse and generate supernova explosions. The understanding of shock acceleration has evolved since the first suggestion by Fermi in 1949 so that it is now based on a well-understood theory [?, ?, ?, ?]. Shock acceleration to hundreds of MeV can be directly observed by satellites in the heliosphere as interplanetary shocks driven by solar outbursts pass by [?].

The challenge now is to identify specific supernova remnants as galactic cosmic accelerators responsible for the higher energy cosmic rays in the GeV to TeV energy range and above. This is difficult because the cosmic rays, being charged protons or heavier ions, are bent by galactic magnetic fields so that they do not point back to their sources. If, however, some of the accelerated cosmic-ray protons and nuclei collide with gas in the neighborhood of their sources, then pions will be produced.

Neutral pions decay to pairs of gamma-rays, and charged pions include neutrinos in their decay products. These secondaries, being neutral, are undeflected by magnetic fields, so they can reveal their sources if enough are produced to be detected at Earth. The paper by Drury, Aharonian and Völk is an early advocate of this approach [?]. The HESS experiment is now making real progress toward this goal, as we have seen at this meeting [?, ?]. Neutrino astronomy is further in the future, but is also well started, as I will mention at the end.

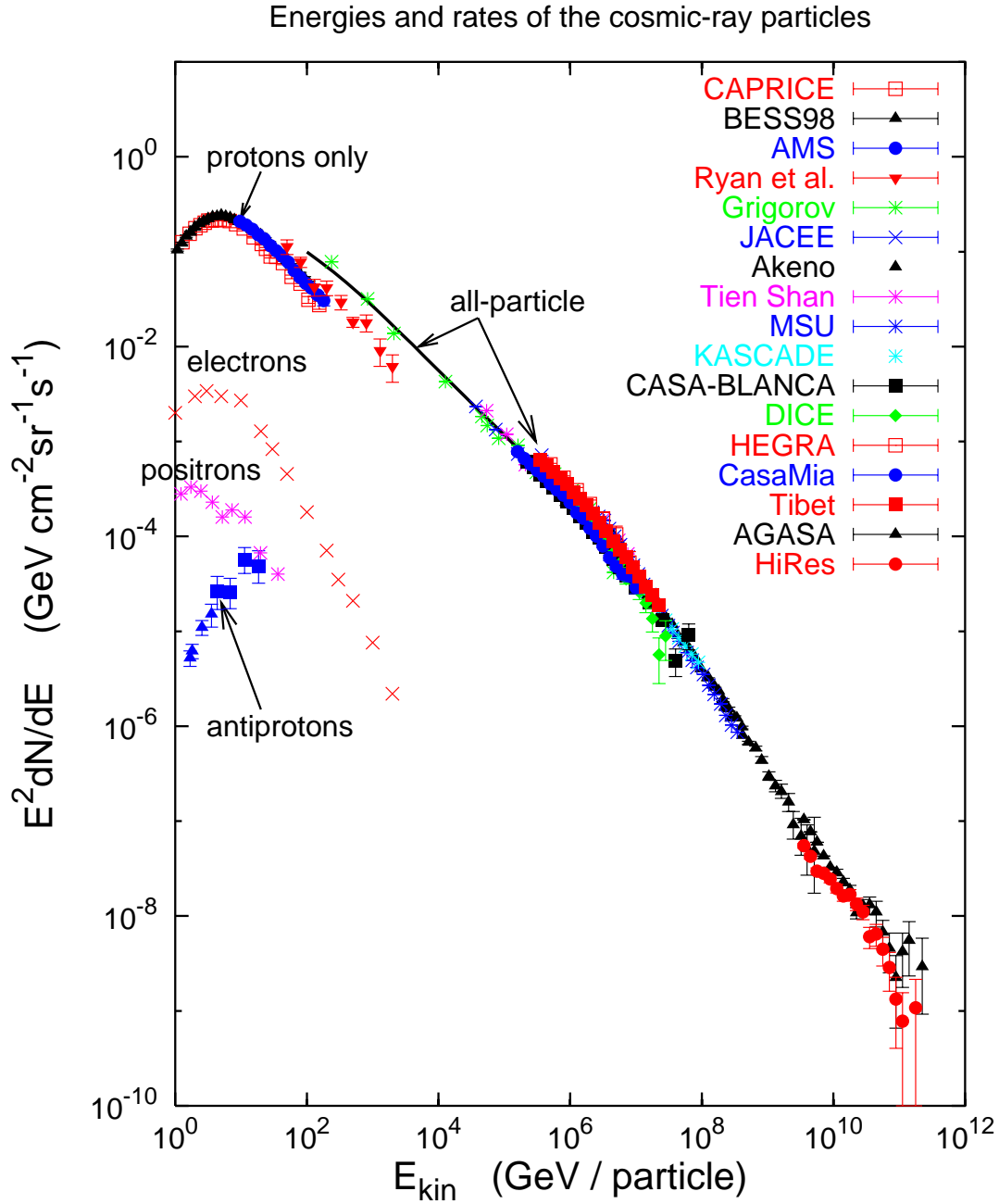
While the general picture of the origin of galactic cosmic rays is now fairly well understood, at least up to energies approaching a PeV, the existence of cosmic rays at Earth from distant sources outside our galaxy is problematic. The frontiers of cosmic-ray science – or particle astrophysics, to give the field its modern name – lie at the extremes of energy and at the interfaces with astronomy and particle physics. What is the highest energy possible in the supernova scenario? Is an additional galactic acceleration mechanism needed to provide an extra boost? Are the highest energy particles from extra-galactic sources? If so, above what energy, and what are the sources? Do we know enough about properties of particle interactions to determine the identity of the highest energy particles, which have energies several orders of magnitude above what is accessible with accelerators at Fermilab and CERN? Is there a suppression of the flux above 100 EeV due to energy losses in the microwave background radiation?

The difficulty in answering such questions about ultra-high energy cosmic rays arises primarily from the fact that they must be studied indirectly by large arrays of detectors on the ground. This is because of their rapidly decreasing intensity as a function of energy, as shown in Figure 1. Detectors small enough to fly above the atmosphere in spacecraft or balloons are simply too small to observe a significant number of primary particles with energies more than 100 TeV or so. Instead the primary composition and the energy spectra of the various components must be studied by observing the cascades produced in the atmosphere by the primary cosmic rays. This is done with detectors on the ground that have a large effective area for sampling the showers.

## 2. The knee

It has long been suspected that the steepening of the cosmic-ray spectrum around 3 PeV has something to do with the upper end of galactic sources of cosmic rays [?]. The top energy for acceleration at supernova blast waves depends on the strength and configuration of magnetic fields in the acceleration region. Classical estimates of 100 TeV for the upper limit for protons [?] have been raised by an order of magnitude in more recent theoretical analyses [?]. If magnetic field amplification occurs at strong shocks, as discussed by Bell at this meeting [?], the maximum energy could be somewhat higher still.

A possible experimental signature for the transition from Galactic to extra-galactic cosmic rays would be a change of composition. Acceleration and propagation both depend on magnetic fields and hence on magnetic rigidity or total momentum divided



**Figure 1.** Global view of the cosmic-ray spectrum.

by charge of the particle being accelerated. Thus, a likely signature of the upper end of one population of particles would be an increase in the relative abundance of heavy nuclei as first protons, then helium, then carbon, etc. reach an upper limit on total energy per particle [?]. The first evidence of such a sequence (which I call a “Peters cycle” [?]) is provided by the recent publication of the KASCADE experiment [?], which was discussed extensively at this workshop. The data from KASCADE are limited in energy to below  $10^{17}$  eV. The larger KASCADE Grande array [?], which encloses an area of one square kilometer, will extend the reach of this array to  $10^{18}$  eV. KASCADE

measures the shower size at the ground, separately for protons and for GeV muons. Inferences from the measurements about primary composition depend on simulations of showers through the atmosphere down to the sea level location of the experiment.

The giant air shower detectors, AGASA [?], HiRes [?] and Auger [?], generally become fully efficient only above  $10^{18}$  eV. Hi-Res is a stereo atmospheric fluorescence detector. As such, it is sensitive to composition through the logarithmic dependence of depth of shower maximum on primary energy and mass  $X_{\max} = X_r \times \ln\{E/A\} + const.$  Using the MIA ground array in coincidence with the HiRes prototype [?], the HiRes group extended their measurement of  $X_{\max}$  down to  $10^{17}$  eV. Comparison to calculations appears to suggest a transition from heavier to lighter primaries already well below  $10^{18}$  eV [?].

### 3. The knee to the ankle

One of the themes of the conference was the question of whether an extra, higher energy galactic component is needed to fill in the gap between the population accelerated by supernova remnants and the turn-on of the population of extra-galactic particles. The background for this question is developed in the review of Hillas [?] and in his talk at the conference. Following Hillas, the extra high-energy population is called “component B”. It is obtained by subtracting two “known” components from the measured spectrum. At low energy, the observed cosmic-ray spectrum is used with an upper cutoff given by the measurement of KASCADE [?]. The extra-galactic component is determined by normalizing to observations above  $10^{19}$  eV with a low energy behavior derived from the model of source distribution and energy loss in the microwave background [?]. There is a gap between the top end of the low-energy component and the bottom end of the extra-galactic component determined in this way that needs an extra component to add up to the observed spectrum.

If such a component B exists, the power required to supply it would give an important clue to its origin. Following the steps used to derive the power requirement for the lower energy galactic cosmic rays, we need to know the propagation history at high energy as well as the spectrum of the B-component. Assuming a cosmic-ray lifetime in the galaxy of

$$\tau_{\text{esc}} = 2 \times 10^7 \text{ yrs} \times R^{-0.33}, \quad (1)$$

where  $R$  is the rigidity in GV, I estimate a total power for the B-component of order  $2 \times 10^{39}$  erg/s. As pointed out in Ref. [?], this is less than 10% of the total power requirement for all galactic cosmic-rays and not much bigger than power observed in individual galactic objects. For example, the Eddington limit for an accreting neutron star is one order of magnitude smaller, while the micro-quasar SS433 at 3 kpc distance has a jet power estimated as  $10^{39}$  erg/s ([?]). Another suggestion is that the gap is filled in by ultra-heavy nuclei [?].

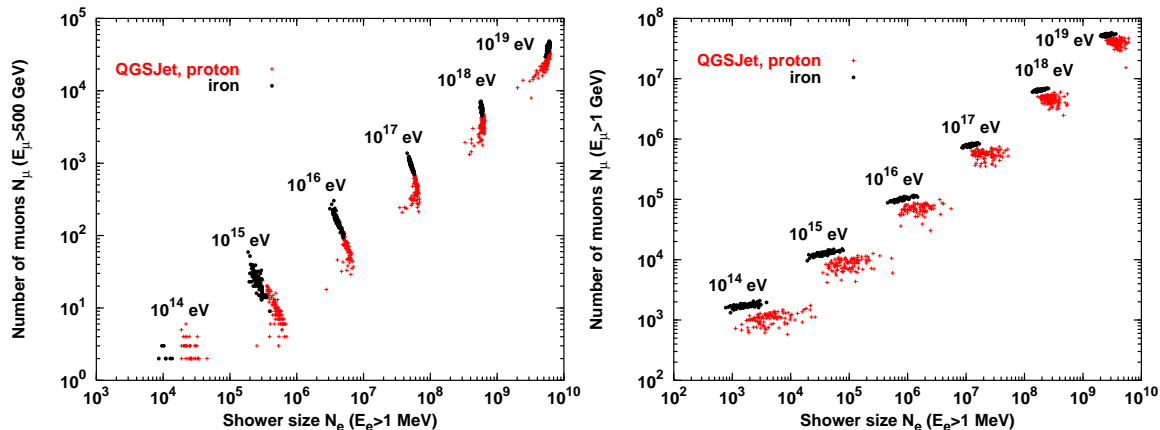
#### 4. New experiments for composition from PeV to EeV

To understand what is going on in this transition region will require a dedicated experimental effort aimed at determining the primary composition in the energy region between the knee and the ankle. The low-energy extension of the Telescope Array [?] and several other possibilities were discussed in talks and working groups during the meeting. An atmospheric Cherenkov detector supplemented by a ground array to measure low-energy muons, as illustrated by the Tunka Project [?], is one possibility. Another is an array of radio detectors, now being explored at Karlsruhe [?] and elsewhere. In this context I describe here the contribution that can be made by IceCube.

The IceCube neutrino observatory, scheduled for completion in 2010, will consist of 4800 optical sensors or digital optical modules (DOMs) installed on 80 strings between 1450 and 2450 m below the surface and 320 DOMs in 160 tanks on the surface, with one pair of tanks near the top of each string [?]. The surface array of IceCube is called IceTop [?]. The plan of IceCube and IceTop and some preliminary results from initial operations were described at this meeting by Serap Tilav. One string with 60 digital optical modules and 4 pairs of Ice Cherenkov tanks, each viewed by 2 DOMs, were deployed in January, 2005 and have been taking data since then [?, ?]. The surface array turns IceCube into a 3-dimensional air shower array with an acceptance large enough to study of composition and energy spectrum to one EeV. The spacing between stations is small enough to achieve good sensitivity starting around one order of magnitude in energy below the knee. The ratio of the shower size at the surface to the signal from penetrating muons in the deep detector is sensitive to composition. The high altitude (3000 m.a.s.l.) of the surface array and the large coverage of the deep array for muons are both advantageous.

There are two main differences between IceCube as an air shower detector and KASCADE-Grande, although both cover similar areas on the surface. KASCADE-Grande is at sea level and measures GeV muons. IceTop is at an effective altitude of 3.4 km. In coincidence with the deep detector, IceCube measures muons of energy above approximately 500 GeV at production. The high altitude of the experiment is an advantage for minimizing fluctuations in the relation between shower size and primary energy.

In his talk at this meeting, Ralph Engel discussed simulations of several air shower observables made with CORSIKA using different hadronic interaction models. His emphasis is on sensitivity to uncertainties and differences among the models. His results can also be used to compare the response of IceCube with KASCADE Grande by using the same interaction model for each detector. Figure ?? shows the number of muons of energy above 500 GeV versus shower size at this altitude. A similar graph for GeV muons at sea level [?] shows fluctuations of more than half an order of magnitude in the relation between shower size and primary energy but a relatively tighter correlation between number of GeV muons and primary mass. Thus the two approaches are complementary, with valuable potential for cross-calibration and elimination of uncertainties arising from



**Figure 2.** Correlation between the number of  $>500$  GeV muons and shower size for showers of different primary energy initiated by proton and iron showers at the altitude of IceTop (left panel). Right panel a similar comparison for an experiment that measures low-energy muons and shower size at sea level. Figures courtesy of Ralph Engel [?] presented at this conference.

the models of hadronic interactions.

Although IceCube is not scheduled for completion until 2010, the deployment plan for December, 2005 and January, 2006 provides sufficient acceptance (area  $\times$  solid angle) to accumulate enough events to reach  $10^{17}$  eV. Thus, if the season plan is accomplished, measurements of interest for the knee region and above could begin in 2006.

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