To higher energy: balloon and satellite investigations around the ‘knee’

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Abstract
The galactic cosmic radiation spans over 14 decades in energy and follows a power law spectrum in energy which shows two features, a steepening in the power law at a few times $10^{15}$ eV—the ‘knee’—and a subsequent flattening in the power law at a few times $10^{19}$ eV—the ‘ankle’. The ‘knee’ was discovered over 40 years ago through the measurement of cosmic ray initiated air showers, yet its origin and the underlying physics remain largely unknown. Experiments over the past four decades, from both balloon and space platforms, have pressed measurements to ever higher energy and to greater precision. This progression is briefly reviewed with emphasis on the current generation of experiments studying the high-energy regime up to the knee using direct particle-by-particle measurements. Prospects for understanding the ‘knee’ in terms of the acceleration of the cosmic rays and possible future experiments are included.

1. Introduction

The galactic cosmic rays are a dilute ‘gas’ of relativistic particles that fill our galaxy and extend well beyond the disc into a galactic halo. A few per cent of the cosmic rays are electrons, which produce synchrotron radiation in the galactic magnetic field, and this radiation provides the means to map the particle distributions. Looking at other galaxies similar to our own, we observe radio synchrotron halos around them as well. The bulk of the cosmic rays, however, are nuclei, consisting of all of the naturally occurring elements from H through U. As with the general galactic abundances, H and He are the most numerous with the heavy nuclei ($Z > 2$) accounting for about 1% of the particles. Recent measurements at a few hundred MeV/nucleon have succeeded in resolving many of the isotopes of the individual elements up through the iron peak [1], giving a detailed picture of the composition of the low-energy cosmic ray beam.

The cosmic rays span an enormous range from near $10^6$ eV to beyond $10^{20}$ eV with an energy spectrum that is a power law over many decades. At the lowest energies, we
cannot observe the particles directly since the outflowing solar wind excludes these particles from entering our heliosphere and being observed at Earth. This heliospheric modulation decreases with increasing energy and introduces a solar cycle variation into the particle intensity at low energy. Beyond about 10 GeV/nucleon, the modulation is small and the cosmic rays follow the energy spectrum (differential spectrum \( \propto E^{−2.75} \)) up to a few times \( 10^{15} \) eV. Here there is a rather abrupt change with the spectrum becoming softer (\( \propto E^{−3.2} \)). This feature is called the ‘knee’ and is illustrated in figure 1. Beyond the knee, the steeper spectrum continues until a few times \( 10^{18} \) eV (the ‘ankle’) where it hardens again and continues to beyond \( 10^{20} \) eV. The region around the ‘knee’, in which the particles are well confined by the galactic magnetic field, holds the ‘key’ to understanding the sources, acceleration mechanisms and modes of transport for the high-energy cosmic rays in our galaxy. It is this region of the energy spectrum which is the subject of this brief review.

2. Historical overview

Cosmic rays are measured with a variety of techniques from many locations: underground, at the surface, high in the atmosphere and in space. The location and technique depend upon the information sought and, most important, the intensity of the radiation. Due to the steeply falling energy spectrum in the vicinity of the knee one expects about one particle per square metre per year. This necessitates detectors of many square metres located on the surface of the Earth. Cosmic rays interact in the Earth’s atmosphere and develop electron–hadron cascades, which spread laterally as they develop and propagate downwards. The total number of particles in these ‘air showers’ is related to the total energy of the primary cosmic ray and to its mass (charge). Thus, by deploying many detection stations over areas of square kilometres, it is possible to study the cosmic rays in the very high-energy region. This was the approach followed historically in the late 1940s and 1950s, which led to the discovery of the knee in the cosmic ray spectrum. Much of this work was done at Moscow State University under the leadership of George Khristiansen, and the ‘knee feature’ could, arguably, be called ‘The Khristiansen Knee’. Air shower arrays were developed in many countries around the world, located at different altitudes from the sea level to mountain tops, to study cosmic rays at or
Table 1. Space instruments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Species</th>
<th>Technique</th>
<th>Energy/ nucleus (eV)</th>
<th>Effective geometry factor (m² sr)</th>
<th>Exposure factor (m² sr days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEZ Proton 1–4</td>
<td>All, H, He</td>
<td>Calorimeter</td>
<td>10^{12}–10^{15}</td>
<td>0.05–10</td>
<td>5–2000</td>
</tr>
<tr>
<td>HNE HEAO-3</td>
<td>1979–1980 16 ≤ Z ≤ 28</td>
<td>Ionization/ Cherenkov</td>
<td>3 × 10^{10}–10^{13}</td>
<td>1.2</td>
<td>370</td>
</tr>
<tr>
<td>French–Danish</td>
<td>1979–1980 4 ≤ Z ≤ 28</td>
<td>Cherenkov</td>
<td>3 × 10^{10}–2 × 10^{12}</td>
<td>0.14</td>
<td>33</td>
</tr>
<tr>
<td>HEAO-3 CRN Spacelab 2</td>
<td>1985 5 ≤ Z ≤ 26</td>
<td>TRD</td>
<td>7 × 10^{11}–3 × 10^{13}</td>
<td>0.1–0.5 (low Z) 0.5–0.9 (high Z)</td>
<td>0.3–3</td>
</tr>
<tr>
<td>Sokol COMOS</td>
<td>1984–1986 1 ≤ Z ≤ 26</td>
<td>Calorimeter</td>
<td>2 × 10^{12}–10^{14}</td>
<td>0.026</td>
<td>0.4</td>
</tr>
</tbody>
</table>

above the knee. One can cite the pioneering work of the Volcano Ranch in the US, developed by the late John Linsley, to Haverah Park in England, to Australia and India and many other countries too numerous to cite. Today, air shower arrays continue to provide data on the highest energy cosmic rays (cf figure 1) and the new arrays have increased tremendously in sophistication and in scale.

The difficulty with air shower observations is in the interpretation of the data. The showers must be modelled in a Monte Carlo simulation, which is then used as a basis for data analysis. The dependence upon the identity of the incident primary particles (the mass A) is found to be weak, so that the composition information is not very precise. In many cases, only H and Fe were modelled and the composition was determined in the form of ⟨ln A⟩. Clearly, experiments that determine both the charge and the energy were desirable, and such direct measurements required deploying apparatus on high-altitude research balloons or in space.

In the 1960s such experiments were developed by Grigorov and colleagues at Moscow State University and flown on the ‘PROTON’ series of satellites. These large ionization calorimeter instruments measured the all-particle spectrum and separately, the H and He components. Balloon experiments began in the 1970s with the flight of ionization calorimeters and Cherenkov counters to measure the spectra of different elements in the range above 100 GeV/nucleon. Continued development in both balloon and space technology led, in the next decades, to the three space experiments: the HEAO-3 satellite, SOKOL on the Cosmos satellites and CRN on Spacelab-2. Using ionization chambers, calorimeters, Cherenkov counters and transition radiation detectors, these experiments pressed the particle-by-particle detection up to energies close to 1 TeV/nucleon and to elements as heavy as iron.

In the late 1970s/early 1980s emulsion chamber technology was developed for balloon flights and several series of such experiments took place—MUBEE, JACEE, RUNJOB—some of which are still publishing results. In the late 1980s the long-duration ballooning techniques were developed allowing flights of 7–14 days, and these became the mainstays of the emulsion chambers, allowing large exposures to be accumulated through yearly flights. In addition, a ring-imaging Cherenkov instrument was flown on a balloon giving a new measurement of the helium spectrum.

A summary of the characteristics of many of these high-energy cosmic ray experiments is given in table 1 for ‘space instruments’ and table 2 for ‘balloon experiments’. Results from many of these programmes have been summarized [2–5] and are discussed, briefly, below.
### 3. Experimental results

Early results from the Proton satellite experiments indicated a possible break, or steepening, in the energy spectrum of hydrogen at energies of a few TeV. Subsequent experiments, however, were unable to confirm such a change, finding a continuous spectrum up to near 100 TeV. However, a spectral difference between hydrogen and helium has been reported as shown by the top two curves in figure 2, which summarizes the measurements of H, He and groups of heavier nuclei [6]. (Note that the flux has been multiplied by $E^{2.75}$ to remove the steeply falling character of the spectra and the plot is in terms of kinetic energy.) The differential spectral index for hydrogen is about $-2.80$ while the index for helium appears to be closer to $-2.68$, based upon the JACEE data [7], giving a two-sigma difference in the index. However, the recent results reported by the RUNJOB experiment [8] show no difference in the hydrogen and helium spectra.

For the heavier nuclei, spectral differences are observed as well. The CNO group shows a harder spectrum than helium as do the medium heavy elements and the iron peak elements. These last two groups have power law spectral indices that appear to be between He and CNO. Extrapolation of this behaviour up to the knee predicts a radically different relative composition as compared to the cosmic rays around 100 GeV/nucleon.

However, we must be careful in the interpretation of the existing data. The current results have been derived from different experiments and, often, many balloon flights of a single instrument have been added together to form an overall dataset. Moreover, the statistical limitations on the current data are evident in figure 2. Clearly, qualitative and quantitative improvements in the experimental situation are needed.

### 4. Particle acceleration in supernova remnants

Cosmic rays and supernovae have long been associated due to the energy input that supernovae can provide. Cosmic rays interact with the ambient interstellar medium as well as escape from the galaxy. The mean confinement lifetime of the particles is about 15 million years [1, 9], so cosmic rays must be replenished. This requires an energy input into cosmic rays of $10^{40}$ to $10^{41}$ ergs s$^{-1}$. This rather large power requirement led, historically, to the presumed connection...
to supernova explosions, which provide an overall power of about $10^{42}$ ergs s$^{-1}$. With 1–10% of this energy appearing as accelerated particles, the cosmic ray energy density can be maintained.

The acceleration mechanism that has become the ‘standard’ for the past several decades is diffusive shock acceleration—first-order Fermi acceleration—operating at the discontinuity where the outward moving blast wave from the supernova explosion interacts with the surrounding medium. Here the magnetic fields confine the particles forcing many crossings of the shock boundary, with the charged particle receiving an acceleration upon each crossing [10]. The acceleration theory has been well developed and tested with direct observations of particles accelerated at shocks within our heliosphere. The theory predicts power law spectra with the same power law index (in magnetic rigidity) for all nuclear species. The expected index is in the range of 2.0–2.2. In addition, there is a maximum energy for the accelerated particles due to the finite lifetime and maximum size of a supernova remnant. For a typical supernova remnant and an assumed magnetic field of 3 $\mu$G, this maximum energy is $Z \times 10^{14}$ eV, where $Z$ is the charge of the nucleus [11].

A comparison of these predictions with the current experimental data shows several major inconsistencies. The spectra of the different nuclear species do not show the same spectral index. The hydrogen spectra show no apparent cut-off at $10^6$ GeV ($10^{14}$ eV), and the corresponding helium maximum energy cut-off at $2 \times 10^{14}$ eV ($5 \times 10^8$ GeV/nucleon) also is not evident in figure 2. The observed spectral index is larger than the theory predicts, but this is due to energy (rigidity)-dependent diffusion/propagation in the galaxy prior to observation at Earth.

Different spectra for different species could reflect the variety of supernova, from ‘bare’ explosions expanding into the local interstellar medium to ‘clothed’ events where the blast
wave interacts with the previously expelled shells of matter from the star [12]. Further, most of the massive stars are formed in groups (e.g., O–B associations) so that the explosion of one star may encounter the remains of shells from earlier supernovae. Matter densities and magnetic field strength are expected to vary in these different environments, so that acceleration beyond the $Z \times 10^{14}$ eV limit cited above is quite feasible. In fact, if the spectra of figure 2 are extrapolated to a cut-off of $Z \times 10^{15}$ eV, summed to form an all-particle spectrum, and compared to the measured all-particle spectrum, the ‘fit’ is quite good to a few times $10^{16}$ eV. This might indicate a shock acceleration cut-off an order of magnitude higher in energy than predicted. However, in this case, the origin of the particles beyond a few times $10^{16}$ eV, the upper end of the knee region, remains to be explained.

5. Understanding a ‘knee’

A representation of the cosmic ray ‘knee’ is shown in figure 3. The steepening of the spectrum is difficult to explain because it signifies the absence of particles.

Extrapolation of the low-energy spectrum results in an increasing (with energy) discrepancy with the steeper portion of the spectrum. This could be explained if a new cosmic ray loss mechanism started becoming important at an energy near that of the knee. Since the particles of this energy (ca $10^{15}$ eV) are well confined in the galaxy, it is doubtful that such a mechanism represents a new propagation loss from the galaxy itself. However, cosmic rays do spend some part of their lifetime in the galactic halo. Suggestions have been offered that interactions with the dark matter in the halo may become important at these energies.

Alternatively, if a new physical channel should open at these energies such that the interaction products were not observable in the air shower experiments, then the observations would show a behaviour such as figure 3, while the actual spectrum in the galaxy would be a continuation of the low-energy portion of the spectrum shown. Suggestions for the production of new, non-standard model particles, or an increased production of high-energy muons, have been offered. There is no evidence at the highest accelerator energies of such ‘new physics’, but these ideas cannot be ruled out until new experiments are performed, probably at the LHC.

A different approach attributes the knee to the termination of the cosmic ray acceleration process, as is expected in models of shock acceleration in supernova remnants. The overall spectrum, however, continues to beyond $10^{20}$ eV, so there must be an additional component or a new acceleration mechanism that provides the particles beyond the termination region. Characterizing such a new component or process is an important task.

Cosmic ray sources/accelerators may involve a variety of astronomical objects or even a plethora of supernova remnants. Since particle acceleration is a common process in any environment in which there are shock waves and magnetic fields, this variety of accelerators may show different maximum (cut-off) energies. Putting a set of such objects together, the
actual spectrum may be one that gradually terminates, declining from $10^{15}$ eV to an end at a few times $10^{18}$ eV. (Beyond this point, the flat part of figure 3, the particles are presumed to be extragalactic.) To reproduce the somewhat abrupt structure in the knee region (cf figure 1) it has been suggested that superposed upon this general terminating spectrum are particles from a nearby source such as a relatively recent supernova [13]. In a model such as this, with the effects of a number of sources/accelerators superposed, one would expect to observe some structure in the measured energy spectra—an observation that could be of critical importance in understanding the origin of the knee.

6. Air shower results

Going to higher energy than the direct measurements requires reliance upon air shower experiments, which trace the knee and beyond in figure 1. The existing data (figure 2) indicate that the relative composition changes with energy. Moreover, the different explanations or models for the knee presented in the previous section predict different relative compositions from $10^{14}$ eV to beyond $10^{16}$ eV. As mentioned earlier, the sensitivity to composition in the air shower analyses is relatively weak, resulting in a presentation in terms of $\langle \ln A \rangle$. Nevertheless, the energy dependence of the relative composition may provide some information on the knee region. A compilation of recent air shower results on composition (cf discussion in [14]) is shown in figure 4, with the results of the direct experiments (dark squares and circles) converted to $\langle \ln A \rangle$ at the low-energy side.

The data from the various air shower experiments shown display an enormous scatter [14], and the two curves show the results of different models. The upper curve predicts a composition becoming increasingly dominated by heavy nuclei, i.e. the lighter components terminate earliest with increasing energy [13]. The lower curve models a scenario in which the SNR acceleration process terminates and a new component, assumed to be hydrogen, becomes dominant, leading to a decreasing $\langle \ln A \rangle$ as the knee is transited [15]. Clearly, some of the current data can support either class of model. What is required is (a) extension of the direct measurements to an energy as high as possible to anchor the air shower results (the shaded region in the centre of figure 4) and (b) improvement of the interpretation of the air shower data. This is the challenge for the coming years.
Table 3. New experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Species</th>
<th>Technique</th>
<th>Energy/ nucleus (eV)</th>
<th>Effective geometry (m² sr)</th>
<th>Exposure (m² sr days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balloon instruments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATIC Antarctic 2002–2003</td>
<td>$1 \leq Z \leq 28$</td>
<td>Calorimeter</td>
<td>$10^{10}–10^{14}$</td>
<td>0.23</td>
<td>6.9$^a$</td>
</tr>
<tr>
<td>TRACER LDB</td>
<td>$8 \leq Z \leq 28$</td>
<td>TRD</td>
<td>$10^{11}–3 \times 10^{14}$</td>
<td>5</td>
<td>70$^b$</td>
</tr>
<tr>
<td>CREAM ULDB</td>
<td>$1 \leq Z \leq 28$</td>
<td>TRD/calorimeter</td>
<td>$10^{13}–5 \times 10^{14}$</td>
<td>1.4–0.35</td>
<td>35–140$^c$</td>
</tr>
<tr>
<td>Space instruments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACCESS</td>
<td>$4 \leq Z \leq 28$</td>
<td>TRD&amp;</td>
<td>$10^{13}–5 \times 10^{15}$</td>
<td>7–12</td>
<td>7000–12 000$^d$</td>
</tr>
<tr>
<td>(CSTRD)</td>
<td>$1 \leq Z \leq 28$</td>
<td>Calorimeter</td>
<td>$10^{12}–10^{15}$</td>
<td>0.9</td>
<td>900$^d$</td>
</tr>
<tr>
<td>PROTON-S</td>
<td>$1 \leq Z \leq 28$ $e^-, \gamma$</td>
<td>Calorimeter</td>
<td>$10^{12}–3 \times 10^{16}$</td>
<td>18</td>
<td>18 000$^d$</td>
</tr>
<tr>
<td>INCA</td>
<td>$1 \leq Z \leq 28$ $e^-, \gamma$</td>
<td>Neutron calorimeter</td>
<td>$10^{14}–10^{16}$</td>
<td>48</td>
<td>48 000$^d$</td>
</tr>
</tbody>
</table>

$^a$ Assumes 30-day long duration balloon (LDB) flight.

$^b$ Assumes 14-day long duration balloon (LDB) flight.

$^c$ Assumes 100-day ultra long duration (ULDB) flight.

$^d$ Assumes 1000 days of full data return.

7. Future investigations

Extending direct particle-by-particle measurements to higher energy, with good charge resolution, is the key to understanding the knee region plus providing a normalization point for the air shower experiments. It is the cosmic ray composition and its energy dependence that will contribute the most to understanding the astrophysics in this energy region. Several new experiments are underway and others are envisioned for the future. These are summarized in table 3.

There are three new balloon instruments. ATIC and TRACER are completed and have had a test flight, ATIC from McMurdo and TRACER from Ft. Sumner. (ATIC flight data analysis is progressing as evidenced by the poster papers presented at this symposium.) ATIC is scheduled for a science flight in December 2002 and is hoping for two circumnavigations of Antarctica for a total flight time of ∼30 days. TRACER is a candidate for an LDB flight (∼2 weeks) in mid 2003. CREAM, which combines the calorimeter technique used by ATIC with the transition radiation measurement employed by TRACER, is a payload for the new ultra-long duration balloon (ULDB) flight program. A new balloon, closed at the bottom, is being developed for the ULDB effort. The plan is to complete many circumnavigations of the Earth for a total flight duration of ∼100 days. All data are to be telemetered to the ground via satellite link, protecting the results from the possibility that the apparatus may not be recoverable. CREAM will fly in late 2003 or 2004 depending upon the readiness of the balloon, flight systems and the instrument.

Even with the ULDB capability, balloon systems still have limited exposure. It would be better to have a space experiment with an exposure of ∼3 or more years. One such investigation is ACCESS, which was proposed to the NASA Explorer Program, MIDEX competition, in this past year. The idea is to put an ∼5 tonne instrument on either a free-flying satellite or on the experiment attach point on the International Space Station. An instrument that was a combination of a calorimeter and a transition radiation detector was proposed. Such an instrument would provide an order of magnitude increase in exposure over the balloon experiments. Unfortunately, ACCESS was not selected in this past round of competition.
We expect another MIDEX competition in about two years (2004), and ACCESS may be re-proposed at that time.

Larger instruments are under development in Russia, PROTON-S and INCA, which would be in the vicinity of 10 tonnes. PROTON-S uses the calorimeter approach, which was successful in the early experiments (see table 1). INCA also uses calorimetry but combines neutron calorimetry with ionization calorimetry to make the measurements. Both the larger experiments would obtain reasonable statistics above $10^{16}$ eV, well beyond the knee. However, these instruments are still in the concept and development phases. No mission, and no launcher, has been identified for these very large payloads, but work is in progress.

In most cases, the new experiments, either balloon or space, involve international collaborations that have been formed to further this important science investigation. Each of the experiments in table 3 was described in the papers at the Hamburg ICRC and the reader is referred to [16] for further details.

8. Summary and outlook

After half a century, the knee remains an enigma! Supernova remnant shock acceleration may well account for the bulk of the cosmic rays below the knee, but these models have difficulty in fully explaining the knee region. In fact, such discrepancies have led to suggestions that the venerable supernova remnant model should be abandoned [17]. With the x-ray data from Chandra revealing details of the CRAB and VELA pulsars [18], there is renewed interest in pulsar acceleration models to complement the supernova remnant process. Also, gamma ray burst sources as well as the galactic centre region should be considered.

The data continue to improve, and we expect new information to become available relatively soon from the balloon experiments, and somewhat later from any space experiment that is approved. The interest remains, since the knee is such a challenging astrophysical problem, and we look forward both to the new theoretical insights and to the improved data from air showers and direct measurements.

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References