Cosmic Ray Questions at High Energy

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The detailed study of the composition of cosmic rays over the last decade or so has produced some significant results leading to major advances in our understanding of the origin and history of these energetic particles. As an example, the ACE explorer mission has shown at ~GeV energies that there is significant time delay (>10^5 years) between the nucleosynthesis and acceleration of these nuclei[1]. This implies that the supernovae which presumably accelerate these particles are not significant contributors to the source material of cosmic rays. At the very highest energies (>3×10^{19}eV) recent results from the Auger project strongly suggest that these particles are mostly extra-galactic in origin. Their directions are correlated with the local structure of active galaxies[2].

However, despite these and other advances at the extremes of the energy spectrum there remain some central issues in cosmic ray science above 100GeV which are unresolved:

- **What is the source of cosmic rays above ~10^{16}eV?**
- **Is there an end of the cosmic ray electron spectrum near 10^{13}eV?**
- **What is the source energy spectrum of nucleonic cosmic rays above 10^{11}eV?**

Cosmic Rays above 10^{16}eV

In the conventional paradigm adopted for explaining cosmic-ray production, energetic nucleonic particles are generated via diffusive shock acceleration in supernova remnants (SNR). The particles remain trapped in the tangled Galactic magnetic field for timescales of ~10^7 years (at GeV energies), and eventually escape or interact with nuclei in the interstellar medium.

While it is a simple and compelling model, something is missing, as is demonstrated in Figure 1, showing a compilation of the measurements of the intensities of cosmic rays at Earth. While the lifetime of strong SNR shock limits the expected maximum particle energy to ~10^{15}eV, the energy spectrum nevertheless

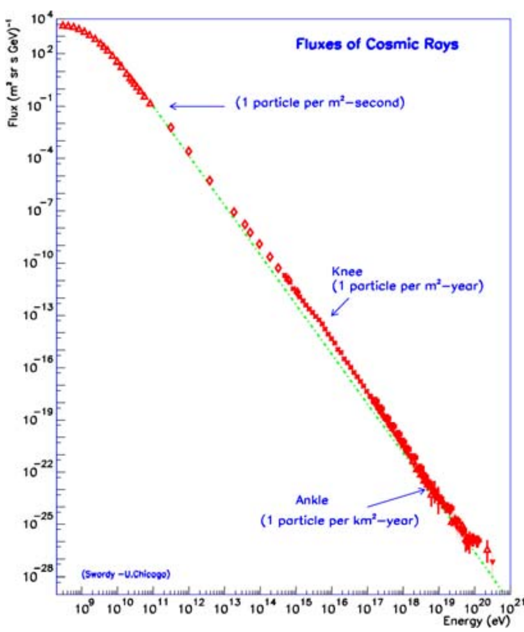

Figure 1. Flux of Cosmic Rays, adapted from [3]

extends without significant features well past this. Although there is a slight steepening in slope, or "knee" coincident with the expected maximum particle energy, the extension of the spectrum is remarkably smooth for several additional decades, until eventually it is overtaken by a presumably extra-galactic component near 10^{19}eV. Indeed, the smoothness of the transition makes it rather unlikely that the post-knee cosmic rays are unrelated to the Galactic cosmic rays of lower energy. But, if so, how do they achieve such energies? While magnetic field amplification and more realistic SNR shock evolution models likely will contribute to the answer, the crucial ingredient required to resolve this issue is the accurate determination of the elemental composition of cosmic rays in the region near the "knee". For example, a significant shift in elemental composition is to be expected if the knee is primarily the result of a series of successive Z-dependent exponential cutoffs. Likewise, a new source of particles from a different mechanism could also have a composition signature.

<u>Electron Energy Spectrum Cutoff</u>

Electrons are also accelerated in standard SNR cosmic ray sources, although apparently with much lower overall efficiency. There may well be more exotic objects such as pulsar winds which make significant contributions to the electron intensity observed at Earth. High energy electrons in the interstellar medium predominantly lose energy through electromagnetic interactions with magnetic fields and ambient photons. Since the rate of electron energy loss scales $\propto$ (Energy)^2 there is a limit to the distance electrons at high energies can travel in our Galaxy. For a typical distribution of SNR sources in our local galaxy, numerical calculations predict a cutoff in the electron spectrum near the region of ~10^{13}eV. The presence of one or more strong, local (~kpc) sources could produce a visible structure in this energy region. The observation of such a structure, or of an electron cutoff would contribute to our understanding of the production and propagation of this important component of cosmic rays. Again, what is needed to make progress here are high-statistics, low-background observations of electrons at high energies, beyond ~10^{12}eV.

<u>Source Energy Spectrum of Nucleonic Cosmic Rays at High Energy</u>

For several decades it has been realized that the measured energy spectrum shown in Figure 1 is probably not the spectrum of cosmic rays produced at the source. This is certainly the case at lower energies (<100GeV), where precise measurements of secondary nuclei have shown that high energy particles escape more easily from the galaxy. The effect of this energy-dependent escape is that the power law form of particles at the source is closer to (Energy)$^{-2.1}$ rather than the observed (Energy)$^{-2.7}$ seen in Figure 1. This harder source energy spectrum is much closer to that predicted by diffusive shock acceleration in SNR and also closer to those values observed recently in new TeV gamma-rays observations of SNR shells. Recent measurements have shown this energy dependence persists into the ~100GeV region[4] but higher energies remain unexplored. A different mechanism must emerge at higher energies because a simple extrapolation of the energy dependent escape into the knee region results in an escape length smaller than the thickness of the galactic disk - which rapidly becomes physically unrealistic. Exploring this issue requires detailed measurements of secondary nuclei to as high an energy as possible in cosmic rays, preferably into the region above ~10^{13} eV.

Observations of Cosmic Rays

The cosmic ray spectrum shown in Figure 1 has such a wide range of intensities that no one technique can span the entire spectrum. Direct measurements of the nucleonic component, on spacecraft and high altitude balloons, are possible, for the most abundant elements, up to energies of perhaps as high as ~10^{15}eV. Beyond this, however, the cosmic ray event rate (~0.1 $m^{-2}sr^{-1}day^{-1}$ at ~$10^{15.5}$ eV) becomes marginal for any practical payload. Above these energies, ground-based ("indirect") detectors enjoy much larger collecting area and consequently much improved statistics. Unfortunately, traditional ground-based detection mechanisms suffer from serious systematic problems arising from uncertainties in the modeling of hadronic interactions in the showers. This makes it very difficult to achieve accurate identification of the elemental identity of the incoming nucleus which caused the shower. Indeed, the only parameter which can be reliably determined by standard air shower observables on an event-by-event basis with reasonable resolution is the particle energy.

Electrons are roughly 1,000-10,000 times less abundant than heavy cosmic rays at high energies. So apart from the requirement of achieving sufficient aperture to collect high energy electrons, the dominant instrumental problem in electron measurements is the reduction of background formed by the overwhelming nucleonic component. In reality this means the proton population must be suppressed by a level of ~10^5 or better to reliably separate electron events at high energy.

The upcoming AMS payload, at present planned for launch to the Space Station in 2010, is mainly designed to measure anti-particles in cosmic rays. It will also allow unprecedented investigation of cosmic ray source spectra into the region of ~500GeV by measurements of secondary nuclei. It will, in addition, deliver high-statistics electron spectra up into the region of ~1TeV. It cannot, however, reach into the "knee" region for nucleonic cosmic rays or provide information on the expected electron "cutoff " region around 10TeV. The existing Fermi gamma-ray satellite has a trigger mode which is sensitive to electrons, but it will have difficulty suppressing hadronic background events to the level required for a clean electron measurement at 10 TeV.

New Techniques in Cosmic Ray Observations

Advances in cosmic ray measurements are driven by better techniques and advances in technology which allow more characteristic details of the events to be recorded. Progress in nuclear cosmic rays at "knee" energies requires a combination of the collecting power of an air shower experiment with the elemental resolution of a satellite experiment. Likewise, for progress on electron science above 1 TeV we need large collecting area and an excellent level of hadronic background rejection. All of these are possible using the new ground-based technique of "Direct Cherenkov" (DC)[5] observations. The DC technique works by making an observation of the Cherenkov light emitted by cosmic ray particles in the upper atmosphere prior to their first hadronic interactions. By exploiting high-resolution pixel (~0.05 degree) Cherenkov imaging, the DC light can be isolated and measured separately from the Cherenkov light produced in the subsequent air shower. Consequently, with every incoming cosmic ray particle, there are two Cherenkov signals – the first (direct Cherenkov) scales with the elemental charge of the particle and is essentially independent of the particle energy. The second Cherenkov signal scales with the particle energy, and is largely independent of the particle charge. This phenomenon has already been used by the H.E.S.S. air Cherenkov array to provide an energy spectrum of iron nuclei at high energy – even though the pixellation (~0.16 degrees) of that instrument is not optimal for the technique.

Fine imaging of air shower events is also expected to provide sufficient shower structure information to discriminate electromagnetic showers from small hadronic showers with much more effect than is possible in presently available ground-based instruments. This can provide accurate identification of multi-TeV electron events from the ground, which will provide sufficient collecting power to examine the "cutoff" region with high statistical accuracy.

The full potential elemental resolution of this technique has yet to be fully explored, but there are indications it could be used to make a measurement of secondary nuclei into the "knee" region. This would provide ground-breaking information on the history of cosmic rays in the galaxy at these energies.

The technology required to fully exploit the DC technique has only become available in the last several years. With the availability of fast FPGA-driven back-ends and the emergence of the latest generation of switched capacitor array front-end ASICs, inexpensive, low-power, pixellated focal plane detectors suitable for Cherenkov light detection are now possible with the large (10k+) channel counts needed for DC observation. Additionally, innovative aplanatic two-mirror optical systems with segmented glass-foam facets, capable of ~10 degree fields of view can provide the required light collection with inexpensive fixed-mount designs. The Direct Cherenkov Observatory (DCO)[6] is an initiative poised to take advantage of these and other new developments in observational techniques. DCO will make significant contributions to all the above science questions and can, by exploiting emerging technologies, be achieved as a small initiative for a cost in the range of ~$20M.

References
[1] Wiedenbeck et al., ApJLett., 523, (1999),L61-L64.
[2] The Pierre Auger Collaboration (2007) Science 318 (5852), 938.
[3] adapted from J. Cronin, T.K. Gaisser, and S.P. Swordy, Sci. Amer. v276, p44 (1997).
[4] Ahn et al. APh., 30, (2008), 133-141.
[5] Kieda, Swordy and Wakely, APh., 15, 287-303.
[6] see http://dco.uchicago.edu