

Workshop on Physics at the End of the Galactic Cosmic Ray Spectrum, Aspen, Colorado, April 2005

Summary Talk: Experiment

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Abstract: This paper summarizes the experimental contributions to the Workshop on Physics at the End of the Galactic Cosmic Ray Spectrum, held at the Aspen Physics Institute, Aspen, Colorado in April 2005. Experimental talks presented during the five day Workshop are summarized. Results of discussions of the Direct Measurement Working Group and the Indirect Measurement Working Group are presented.

1.0 Introduction

Experimental evidence has suggested for some time that, while lower energy (SN remnants) and ultra-high energy (extragalactic AGN and top down) processes) were at least reasonable candidates for the origin of cosmic rays, the region from the knee of the spectrum to the ankle was much more difficult to interpret, even in terms of very simple phenomenological models. This can be termed the puzzle of the “missing middle” in cosmic ray physics. If the spectrum just beyond the knee is due to new galactic sources, spectacular fine-tuning is required to make the knee such a smooth and downward turning feature. “Re-acceleration” models [1], which reprocess the low energy cosmic rays, solve the continuity problem but have major problems of their own. Injection of extragalactic cosmic rays down to the knee tends to produce very large extragalactic cosmic ray fluxes just outside the galaxy and in any case fail to explain higher energy features such as the second knee.

This “missing middle” puzzle re-emerged in this workshop as a kind of theme. In terms of experiments, the difficulty in understanding what is missing results from the fact that we approach this middle from below and from above. The low energy and high energy experimental techniques are being pushed to their upper and lower limits and they do not overlap to provide believable cross-calibration.

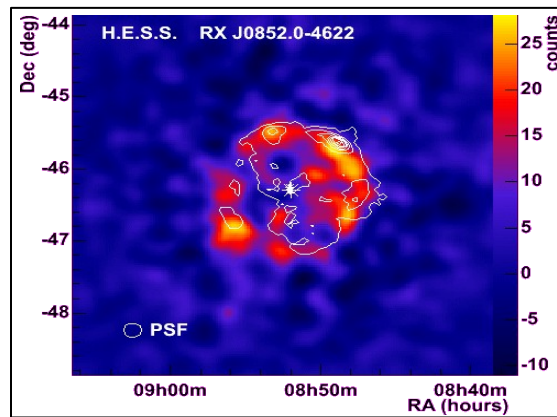


Figure 1. Observation of TeV gamma ray emission from RX J0852.0-4622 supernova remnant by HESS collaboration.

2.0 Direct Measurements

New results from TeV gamma-ray astronomy (HESS) [2] show the importance of new experiments with better sensitivity and energy resolution as well as the important interplay between the neutral and charged components of the galactic cosmic ray radiation in terms of understanding the physics involved (see Fig. 1). While the SN remnant model has for many years been supported on the basis of the energy requirements to sustain the total charged cosmic ray flux below the knee and the approximate agreement with the overall power-law spectrum index, direct observation of extended objects in the Galaxy by HESS, associated in many cases with identified SN remnants has ushered in a new era in this field. While the “smoking gun” connecting observation of TeV gamma rays from these sources with charged cosmic rays is still not in hand, there are detailed models of such SN remnants [3] which also predict the X-ray and radio signals observed and acceleration of charged particles is certainly consistent with what is seen. The HESS results will very likely lead to conclusive demonstrations that the galactic cosmic ray spectrum sources below the knee are largely associated with these objects. Of particular interest is the fact that there is no sign of a cut-off in the rather hard energy spectra of these sources. Observing such a cut-off would be of great importance in understanding how high in energy the acceleration process can go. This will likely require a new generation of detectors with sensitivity to 100 TeV gamma ray fluxes. TeV gamma ray astronomy may thus be moving to near PeV energies, just below the knee of the charged particle spectrum and may have even more direct implications for this field in the future.

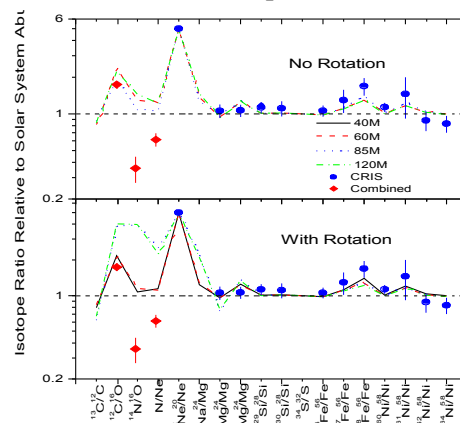


Figure 2. Results from ACE isotopic spectrometer on ratio of observed isotopic cosmic ray abundances to ISM abundances. Lines indicate predictions of Wolf-Reylet star wind models for the case of spinning and non-spinning stars.

Bob Binns presented very interesting results regarding the isotopic composition of low energy galactic

cosmic rays. The results from the ACE spectrometer [4] on the ratio of isotopic abundances to the ISM abundances show large excesses for Carbon and Nitrogen isotopes (see Fig. 2). These are precisely the isotopes produced in the region of Wolf-Raylet (WR) stars. It has been suggested that galactic cosmic rays, while originating in SN remnants can be reaccelerated in WR winds [5]. SN's and WR stars tend to cluster together in “superbubbles” in the galaxy. The observation of deviation from the ISM isotopic abundances strongly reinforces the assertion that a substantial part of low energy galactic cosmic rays are formed in superbubble regions of the galaxy.

At somewhat higher energies, resolution becomes coarser, until with ATIC, JACEE and RUNJOB, broad categories of nuclei are associated together and isotopic analysis is impossible. Preliminary ATIC results (see Fig. 3) [6] indicate the proton and He spectra have very similar power indexes, while the Iron group shows some flattening of the spectrum. At the highest energies accessible to the experiment, the heavy ion spectra show deviations compatible with a modified Leaky Box Model. ATIC has an energy reach up to 10^{13} eV for light (p and He) and 10^{12} eV for heavier nuclei.

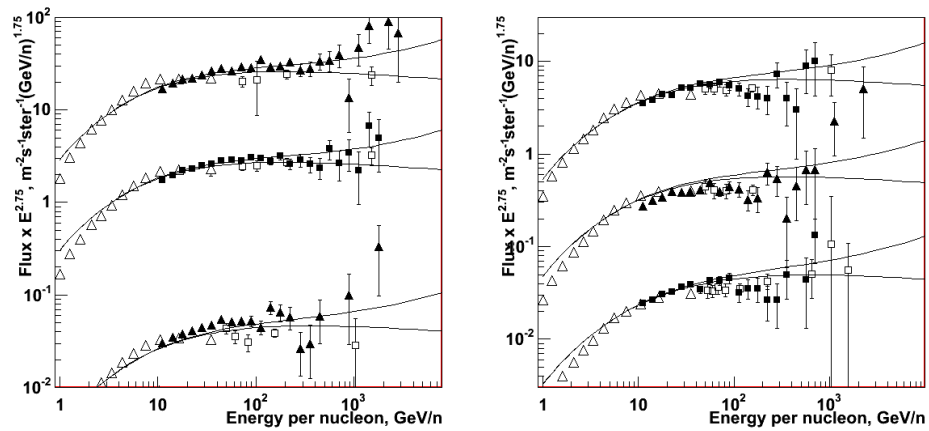


Figure 3. ACE results on spectrum of heavier nuclear groups

RUNJOB presented final results on their work [7], extending the energy reach of 10^{14} eV/nucleon. While there is reasonable agreement within statistics with the long-standing JACEE results for many of the nuclear groups, there is significant disagreement about the normalization of the Helium flux (see Fig. 4). This is significantly lower than what JACEE finds, both in absolute terms and in terms of the He/proton ratio. The nature of this unfortunate disagreement remains unclear.

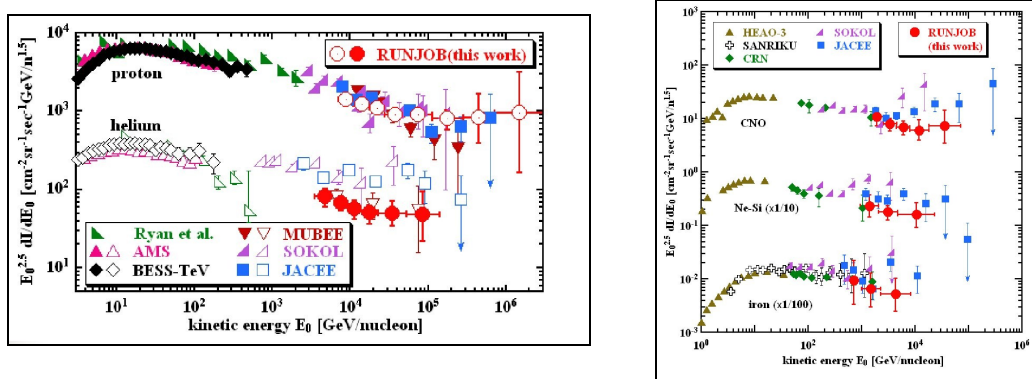


Figure 4. Final RUNJOB results on proton and He and heavier nuclear spectra.

With this exception, ACE, JACEE and RUNJOB data generally indicate continuing power-law spectra for

the nuclear constituents with no hint of a turnover up to energies of near 10^{14} eV. Within errors, the power-law indices for the different nuclear groups also appear to be similar.

3. Indirect Measurements, the Knee Region

Above this energy, indirect detection using surface arrays of various kinds must be used. Fig. 5 shows the very clear evidence for a second knee in the total particle spectrum in the region of 3 to 5×10^{15} eV. It would be very important to trace the origin of this knee in the individual nuclear spectra, but present direct experiments simply do not have the statistical reach while ground based arrays do not have the resolution in A needed. Note that the normalization jump between CASA-BLANCA and all the other experiments may reflect an energy scale shift between these experiments, because in such plots the differential spectrum is multiplied by a power of the energy. It is interesting to note that BLANCA and TUNKA use similar Cherenkov techniques and yet differ in normalization, so the issue is not simply related to charged particle vs. Cherenkov light detection systematics.

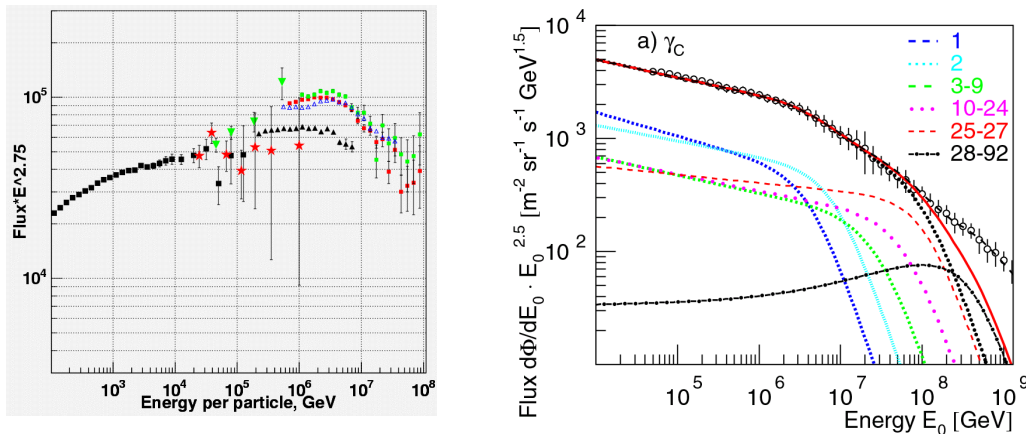


Figure 5. Total charged particle spectrum in region of the knee.

Figure 6. Horandel’s model of individual nuclear group rigidity dependent cut-off spectra adding up to the total charged particle spectrum in the region of the knee. Note the deficit above 10^{17} eV.

The change of slope representing the knee is seen in all experiments. Hoerendal [8] has interpreted this result by extending the direct nuclear group spectra measurements with a phenomenological model. His model (see Fig 6) assumes a rigidity dependent cutoff for each nuclear species and either a common final spectral index (γ_c) or a common change in the final spectral index ($\Delta\gamma$) after the cutoff. In both cases, a consistent picture emerges of the extrapolated nuclear species cutting off at various energies and together forming the “knee” of the total spectrum. In this way, the cosmic ray spectrum up to about 10^{17} eV/nucleon can be “understood”, assuming that the SN accelerator can provide the necessary maximum energy. Of course, it would be crucial to actually measure the turnover in the nuclear species to confirm this picture.

The Cascade experiment [9] has attempted to do this by making very careful measurements of the electron and muon content of EAS from near the knee to about 10^{17} eV/nucleon. However, interpretation of the Nmu vs. Ne measurement requires a model for the hadronic interactions. The available models, QJS-jet and Sibbyl lead so somewhat different results for the lower mass nuclear groups (see Fig. 7). While the qualitative behavior of the light nuclear group spectra seems reasonable, i.e. they have cut-off energies that make sense when compared to the rigidity dependent model predictions, the details are model dependent. When one looks at the heavy nuclei, the situation is much worse, with very different results for the two models.

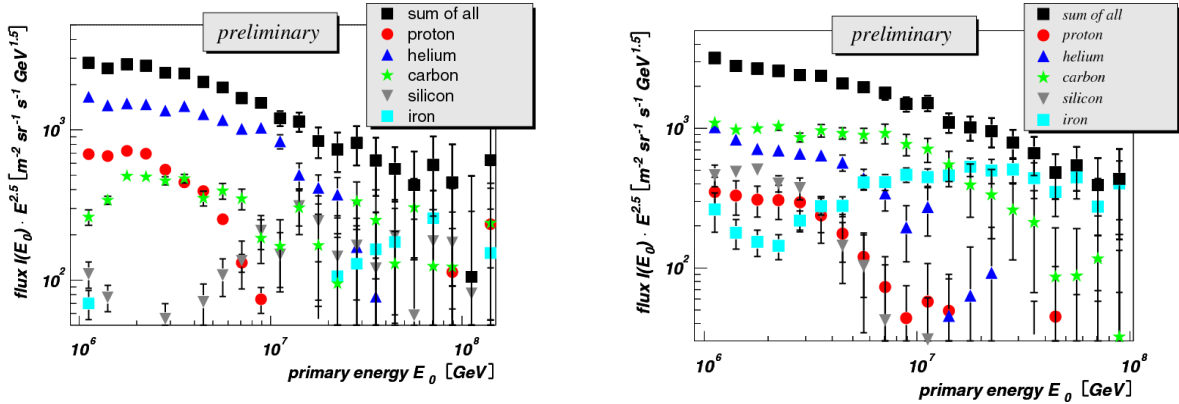


Figure 7. Cascade experiment deconvolution of individual nuclear group spectra using the QJS-Jet (left) and SYBILL (right) hadronic models.

4. The Second Knee and the Ankle

Moving to higher energies, four different experiments have seen evidence for a break in the spectrum between 10^{17} and 10^{18} eV [10]. This “second knee” is particularly evident if the energy scales of the four experiments are adjusted so that their flux normalization just below the knee energy are consistent (see Fig 8).

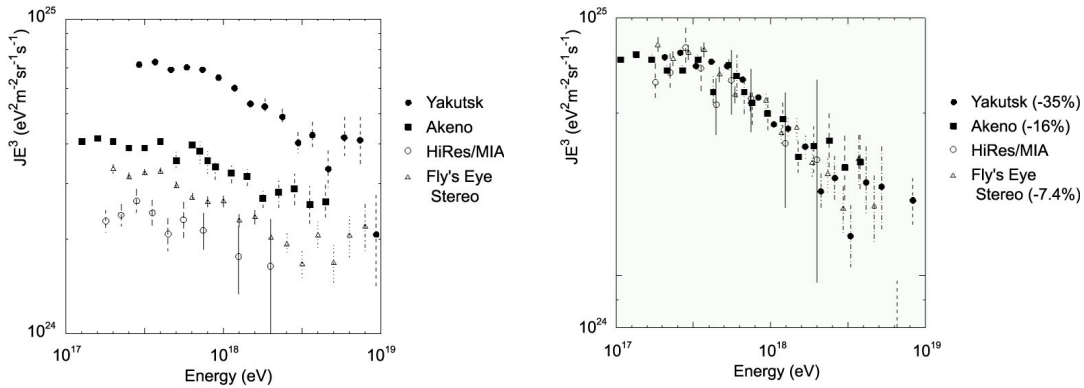


Figure 8. Evidence for existence of second knee. Left side of figure shows spectra from four experiments. Right side shows energy scale shifted spectra such that the flux normalization below the second knee is in agreement.

In the energy decade just above this feature, another feature called the ankle has now been very clearly observed by the HiRes experiment [11] (see Fig. 9), though it has also been previously reported by HP, Yakutsk and the Stereo Fly’s Eye experiment [11]. At the same time, composition measurements [12] via the so-called elongation rate of Xmax (Fig 10) reported by the HiRES/MIA and Stereo HiRes experiments show what is consistent with a transition from a “heavy” composition below the second knee energy region to a “light” (essentially protonic) composition above 10^{18} eV and extending through the region of the ankle. What is the interpretation of these features?

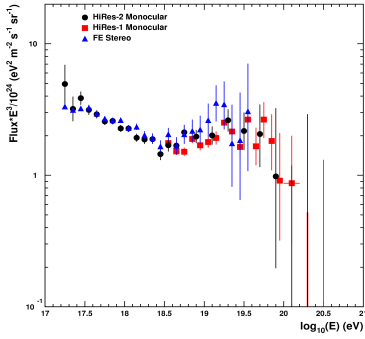


Figure 9. Ankle and GZK structures seen by Fly’s Eye Stereo, HiRes I mono and HiRes II mono data.

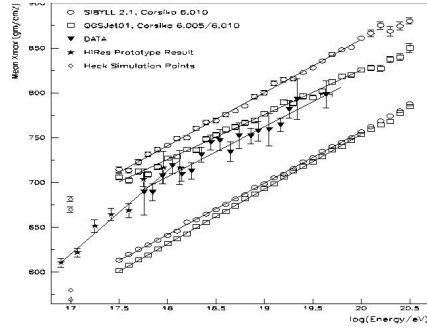


Figure 10. Elongation rate measured HiRes-MIA and HiRes Stereo Experiments.

Previous interpretations of the ankle structure assumed that it represented the termination of a “heavy” galactic cosmic rays spectrum and the emergence of a harder “light” extragalactic spectrum in the $3 - 5 \times 10^{18}$ eV region [13]. Newer composition data, and a clearer view of the second knee has led to a new view of what is happening in this energy region. The second knee, in this view, represents the end of the galactic cosmic ray spectrum, while the ankle is due to the e^+e^- energy loss process of extragalactic protons on the 2.7 deg. black body radiation [14]. At higher energies, (6×10^{19} eV), interactions of these protons with the microwave background leads to the appearance of the GZK cutoff due to inelastic pion photoproduction [15]. Fig. 11 shows the expected spectrum from a simple model incorporating many of these features. The effects of the various processes are more clearly seen in Fig 12 where the contributions of sources in shells of constant z to the spectrum observed on Earth is shown. This figure also shows that the structures in the spectrum, if indeed they can be identified with these mechanisms, are sensitive to the distribution of CR sources as a function of z and hence to the cosmological evolution parameters [16]. This new view might be termed an “early transition model” since the cosmic ray flux would then be dominated by extra-galactic particles as early as 3×10^{17} eV.

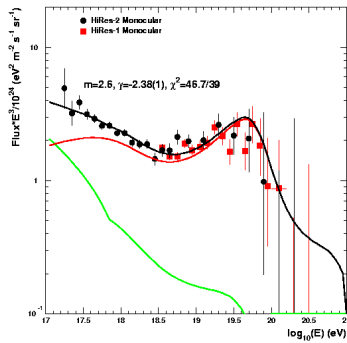


Figure 11. Result of a simple two components model with a “heavy” galactic cosmic ray spectrum and a “light” extra-galactic spectrum. The relative normalization of the two spectra is determined by the measured elongation rate.

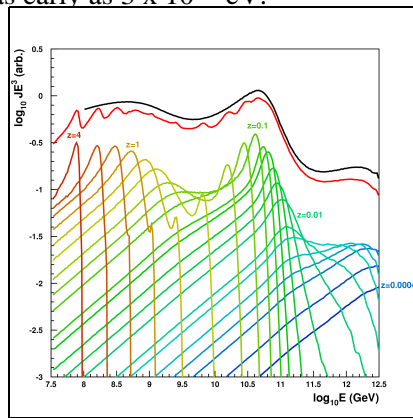


Figure 12. Contributions of shells in constant z to the total extra-galactic spectrum. Note that the injection spectrum here is $E^{-2.7}$.

Berezinskii presented a particularly cogent summary of this approach [17]. In his view, the ankle structure is actually a more robust indicator of the propagation of protons through the black-body radiation than the GZK cutoff itself. He states that the location and shape of the dip appears to be

independent of the details of the nature of propagation (diffusive or rectilinear), source distance distributions (source isotropy) and fluctuations in interactions. The GZK feature is sensitive to all of these and could in principle even reflect the maximum energy of the acceleration source instead of a propagation effect. One very strict requirement for the truth of this interpretation, however, is that the composition of cosmic rays in the ankle region be light. If a significant heavy component is found, this interpretation would fall into difficulties.

There is also an implication about the origin of the second knee. While a natural assumption would be that the second knee represents the maximum energy of the galactic flux, i.e. that the slope change is primarily due to galactic flux changes, Berezhinskii points out that the total galactic + extragalactic flux would exhibit a knee around 10^{18} eV due to the transition from adiabatic to e^+/e^- energy losses in the extra-galactic spectrum. Again, a way of separating galactic and extragalactic flux in this energy region would be very important to check this assumption.

This model still does not address the nature of the galactic flux in the second knee region. As seen below, rigidity dependent models normalized to low energy direct data cannot explain the existence of galactic flux out to the second knee. Hoerendal has even suggested that ultra-heavy nuclei such as Uranium may be required to fill the gap. Hillas [18] has suggested the existence of an unknown “component B” (i.e. non SN relic related component) in the galactic spectrum to explain the same phenomenon.

While this picture is certainly compelling and allows us to make sense of the structures and transitions seen, it depends very much on the success of detailed fits to the data and to the identification of “heavy” and “light” components with galactic and extra-galactic fluxes respectively. The data, however, comes from a number of poorly overlapping experiments and systematic effects may be very important. The HiRes-MIA experiment, for example, utilizes a hybrid fluoresce- ground-array reconstruction technique, while the HiRes Stereo result utilizes simultaneous observations of EAS from two widely separated stations. The two experiments barely overlap in energy range and the important transition from “heavy” to “light” is not seen in overlap. Similarly the ankle structure reported by HiRes is seen only in poorer resolution monocular data, since the Stereo HiRes aperture is changing so rapidly that the effective physics threshold for Stereo data is 3×10^{18} eV, right in the middle of the ankle region. So while the new interpretation is of great interest, the data underlying it may suffer from systematic effects that need to be understood. Ideas on how to improve the situation are discussed below.

5. Results from Working Groups

A significant part of the workshop was devoted to new ideas for experiments. Two working groups, one on direct low energy experiments and one on indirect experiments met to try to formulate reasonable scenarios for addressing the known problems with the present data. A theory working group also met, but its conclusions will be discussed in the theoretical summary talk.

5.1 Direct Measurement Working Group

How can the shortcomings of the low energy data be addressed? The long planned ACCESS proposal for the ISS has become an unrealistic dream, at least for foreseeable future. The direct measurement working group addressed the prospect of balloon and ground based measurements that would have similar sensitivities to the ACCESS proposal and came up with two interesting ideas. Balloon borne transition radiation detectors could in principle be increased in area to 5 x 5 m. In this case 10 long duration balloon flights would have similar sensitivity to ACCESS for heavy nuclei. For protons and helium nuclei, balloon borne instruments cannot reach the ACCESS goal. However a very high altitude mountain calorimeter, similar to the Cascade calorimeter, could study the surviving single proton interactions with an effective geometric factor very similar to ACCESS's. In this case, ACCESS sensitivity might be achievable in less than a year's data collection. Of course, these measurements would have significant contamination problems due to interaction in the upper atmosphere, but these were deemed survivable. A

combination of these two techniques might move the “direct detection” measurement of cosmic rays, with reasonable statistics, to a maximum energy of 10 eV.

5.2 Indirect Measurement Working Group

Even such improved direct observation will not lead us to the knee. The crucial issue is to make believable spectral measurements for the different nuclear groups up to the point where the maximum acceleration energy of each group is seen. The indirect measurement working group considered a design for an experiment that would overlap with direct measurements below 10^{14} eV and extend to overlap with fluorescence measurements at $10^{16.5}$ eV. The idea here is to combine the Kascade-type measurements of EAS electron and muon density with Xmax information provided by a measurement of the Cherenkov lateral distribution a la BLANCA. While Kascade composition results are very model dependent, the addition of Xmax information on an event-by-event basis can both be used to reduce the effect of fluctuations and to impose an additional experimental constraint on the models used. Comparing theoretical predictions with data in a three-parameter space was considered the only presently accessible way to deal with the model dependence problem.

Figure 13 shows a schematic view of such a hybrid detector (dubbed Cherenkade) combining muon detectors, an infill array primarily sensitive to electrons and a BLANCA [19] type Cherenkov detector array. The 3 km by 3 km array would have plenty of statistical reach to overlap proposed TA low energy extension fluorescence measurement of Xmax, BLANCA itself operated down to 10^{14} eV so that overlap with direct measurements should not be an issue.

Another possibility is to use the ICETOP array [20] (see Fig. 14) currently being built over the ICECUBE detector at the South Pole. This array consists of frozen water Cherenkov detectors, which in principle can separate out the electron and muon components. The addition of a Cherenkov detector to this surface array could allow important composition measurements to be made. The presence of ICECUBE below the ground array would also allow measurement of the multi TeV muon component of the EAS, further constraining the composition model.

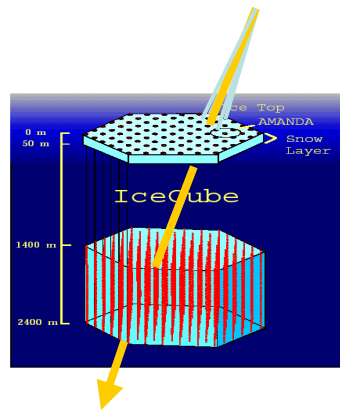
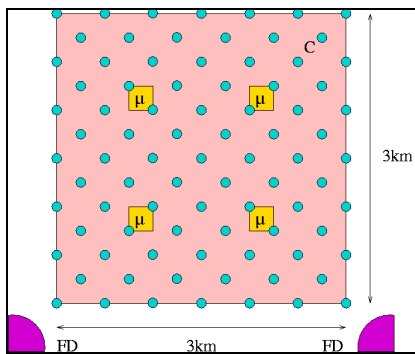


Figure 13. Cherenkade detector. Circles Represent Cherenkov detectors, Squares are muon detectors.

Figure 14. IceCube detector with Ice-top array.

Another possibility that was discussed is to use a DICE [21] type of detector to find the Xmax of a shower. Here Cherenkov light is detected by at least two imaging Cherenkov telescopes and the detailed distribution of light in each telescope allows the stereo reconstruction of the shower’s position in the atmosphere. Roughly speaking, the centroids of the two images define the position of shower maximum. Since one possible result of the HESS experiment is the development of proposals to build telescopes that increase the range of TeV gamma ray detectors to 100 TeV or more, these same telescopes, if their field of view can be made sufficiently large, can study the charged cosmic ray background in this manner. In

principle, gamma ray telescopes can be combined with Cascade type ground arrays to determine the electron and muon content of the EAS as well.

At energies above 10^{17} eV, fluorescent detectors have the major advantage of directly determining shower X_{max} and having a model independent, calorimetric energy reconstruction. The problem with existing fluorescence detectors such as HiRes and Auger is that they were designed with $> 10^{19}$ eV physics in mind. The HiRes stereo detector has a physics threshold of about 3×10^{18} eV, while the hybrid Auger detector cannot study X_{max} in an unbiased way below 10^{18} eV. Special fluorescence detectors detection of shower maximum down to $10^{16.5}$ eV. A proposal to do this is included in the TA/TALE detector study presented at this conference. Here, a suite of detectors whose response overlaps in energy makes possible a nested set of experiments that extend from $10^{16.5}$ eV to beyond 10^{20} eV. The primary TA detector (see Fig.15) consists of a ground array of 560 scintillation counters spaced by 1.2 km and overlooked by three air fluorescence detectors. The detector will operate as a stand-alone ground array, primarily sensitive to the electron component of the shower (similar to AGASA but ten times larger), as a hybrid detector, and as a stereo and mono air fluorescence experiment. This part of the experiment is designed to study the $> 10^{19}$ eV cosmic ray flux, with particular emphasis on the GZK cutoff and the region just below.

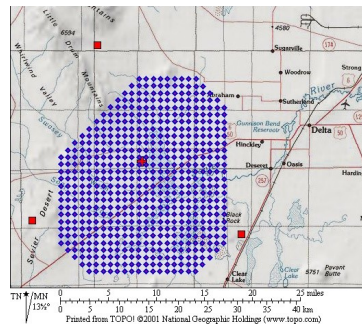


Figure 15. Schematic view of Telescope Array (TA) detector. Blue squares indicate location of ground array counters. Red squares are at the location of Fluorescence detectors. Red square at the center is the central laser facility for monitoring the atmosphere.

The detector will be augmented by two additional fluorescence detectors forming stereo pairs with two of the primary detectors (see Fig 16). These stereo pairs have spacing optimized to study the cosmic ray spectrum in the ankle region – from 10^{18} to 10^9 eV. Finally, a special tower detector looking high in the atmosphere will be combined with an infill 400 m spacing ground array to extend the hybrid fluorescence response down to $10^{16.5}$ eV. The apertures of the three parts of this experiment are slowly varying in their respective energy regions of interest so that the systematic errors in spectrum shape will be well controlled. Furthermore, the resolution in X_{max} and energy will remain essentially constant over the entire energy reach of this experiment. Similar ideas have been proposed for the S. Auger array in order to extend its low-energy response, though these plans are not as developed at this time.

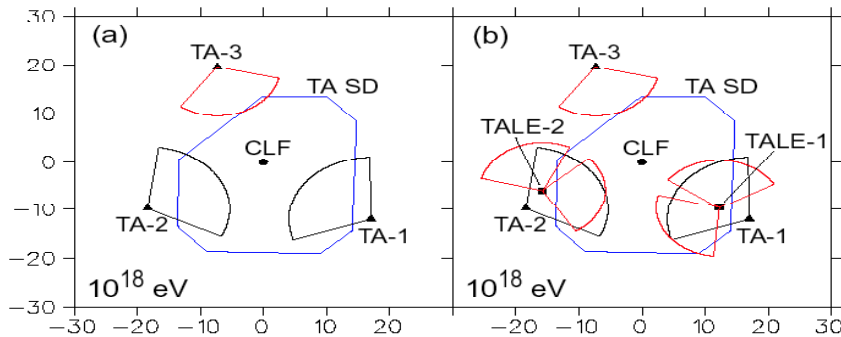


Figure 16. Schematic of TA stereo detectors: Left shows the three primary TA fluorescence detectors and array. Right shows the additional two fluorescence detectors located to form two stereo pairs. Shown in outline is the approximate aperture for 10^{18} eV

6. Conclusions and Summary

This workshop reviewed the very broad range of physics implied by the study of the galactic cosmic ray spectrum. At the lowest energies, this requires the confirmation of SN remnants as the source of galactic cosmic rays. The HESS results go a long way to re-enforcing the validity of this model but can still be interpreted as only having to do with electromagnetic component (gammas and electrons). It will be important to find a real “smoking gun.” And this may require the extension of telescope sensitivity to near 100 TeV energy in gamma rays. The recent data on association of low energy galactic cosmic rays with “superbubble” areas on the galaxy enriches the possibilities for acceleration, while maintaining a close tie to the SN paradigm. While new information on the spectrum of the charged particle species up to near 10^{14} eV is now available from RUNJOB, it is clear that there are still unresolved systematic issues, especially with the He component and that statistics are still so poor at the highest energies as to preclude and definitive statements about changes in slope of the nuclear spectra near the knee.

The knee, while now well established in the all-particle spectrum is just beginning to be seen in the individual nuclear species. Cascade has clearly demonstrated the existence of knees in the proton and He spectra but the heavier nuclei yield results that are too model dependent to be reliable. Thus the nature of the heavy galactic cosmic ray spectrum above the knee and up to 10^{17} eV is still not well understood. Above 10^{17} , three distinct features of the all-particle spectrum are now clearly confirmed – the second knee, the ankle and the GZK cutoff. While there may still be a trickle of events beyond the GZK cutoff, the expected bump structure is clearly there. New interpretations of these structures and the associated data on composition change lead to an interpretation of an “early onset” of the extragalactic cosmic ray flux. This in turns leads to interesting possibilities of doing cosmology with charged particle cosmic rays. However this interpretation depends heavily on composition measurements, which must be made more reliable.

As indicated in the introduction, the “missing middle” is very much with us. While much progress has been made at the lower and the highest energies, improving the experimental reliability of indirect measurements from the knee to the ankle will be of prime importance in the next decade of work on the difficult but very rewarding problem of the nature of galactic cosmic rays.

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