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Understanding the Knee

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For decades, the details of the spectrum and the primary composition in the neighborhood of the "knee" have been studied by many different groups. It is discouraging that there is not yet a final, agreed-upon spectrum and <lnA> vs. E in this region. I proposed that the different groups share their analysis procedures, and see how dependent their results are on the analysis programs. Only when very different data sets (at different elevations, with different muon arrays, etc.) yield the same results when analyzed by the same programs will we have confidence in the analysis procedures and in the results. This conference should provide an excellent communications venue to initiate this exchange.

1. The problem

The chaos surrounding the cosmic ray community's reports on the primary cosmic ray spectrum and mass composition around the knee (e.g. over the energy range between 0.1 and 100 PeV) is really an embarrassment, considering the time and effort spent on these problems and the number of different arrays and observations represented. Of course it is universally understood that the problem arises from the three simultaneous unknowns: the primary spectrum, the composition vs. energy, and the primary interaction physics, plus the fact that the low primary flux at these energies requires indirect observations at ground level, where large-area detectors are practical. The broad diversity of observational technologies and of location (depth in the atmosphere) of the arrays employed for these studies is encouraging, but their lack of agreement is disappointing. To be sure, all observations agree that there is a knee, i.e. that the spectral slope increases significantly at energies above about 3 PeV from an exponential slope of about –2.7 to a slope of about –3.1. And most of the analyses of the composition, especially the more recent studies, agree that the primary composition becomes heavier as the energy increases through this energy region. However the spread in these conclusions is very discouraging.

Granted that each experiment is different, at a different elevation, with different counter technologies, different depths (energy thresholds) of muon detectors, etc. And it is certainly agreed that the primary interaction model is uncertain, hence some groups use QGSJet, others SIBYLL or NEXUS, etc., although many of the studies compare their data with predictions of two or three interaction models. The development of the cascade in the atmosphere is generally modeled with the CORSIKA or MOCCA programs, on which the community seems to agree, and which are based primarily on lower-energy, established experimental data.

2. The spectrum

Although different all-particle spectra, reported by different groups, vary by about a factor of two at a few PeV, because of the steeply-falling spectrum, this variation could be entirely resolved by adjustments in the energy calibration of the different reported results with a total range of only 15%. This and many related issues are discussed in the excellent 2003 paper by Heinigerd Rebel and his Karlsruhe colleagues [1]. It is possible that one source of normalization uncertainty – and disagreement between different experiments – could be due to the different sensitivity of air shower scintillation counters to gamma rays in different arrays, and to an inadequate calculation of this gamma sensitivity. There are about a factor of 6 more gammas than electrons in air showers. The thin plastic scintillators typically used in shower arrays are largely transparent to them, and it is tempting to calculate the shower sizes and energies primarily based on the assumption that only electrons are being detected. The gamma conversion in the counter housing (steel, aluminum, etc.) must be considered, and also in the photomultiplier plus its base and electronics, in the case of those arrays with the phototubes mounted above the scintillators.

The calculation of the primary energy from the shower data also varies between groups. For example, the CASA-MIA group used a formulation: N(e)+KN(mu)=CE. They found, from Monte Carlos, a value of K such that the energy determined in this way was the same for Fe and proton primaries. They determined a value of K of 60 for a best fit for vertical showers, increasing to 64 for about 37 degrees [2]. The GAMMA group, on the other hand, has used a different formulation, based entirely on the air shower data [3], and using the "alpha parameter" method, based on the lateral characteristics to determine the age, plus the NKG function, to determine the total energy [4]. Again, this appears (from MC studies) independent of primary composition, and gives the same flux and spectrum out to zenith angles of 30 degrees. As summarized by Huangs et al. [1], other groups use different methods.

It would seem desirable and informative for different groups to calculate the incident shower energy by two (or more, perhaps) methods, and see the extent to which they agree. Although the different detector stations are at different altitudes, the different energy calculations can be appropriately modified for each. This will require a close communication and collaboration between the different groups, but the outcome should be very positive, and worth the effort.

3. Composition

The ambiguities in the different determinations of composition may be more difficult to resolve. Typically, the ratio of the muon number to the electron number in an event is used as a measure of the composition, with heavier primaries producing relatively more muons. It appears that the groups using this approach generally agree on an increase in <lnA> through the knee region, and this would appear compatible with the plausible idea that the break in the primary spectrum is similar for each rigidity, so that the heavier primaries have their knee at higher total energies. However observations of the elevation of shower maximum, with Cherenkov detectors, seem to give a different interpretation. In any case, as in the case of the spectrum measurements, it would seem desirable for different groups to exchange their data, or to exchange their analysis programs, to explore to what extent their determinations of average mass (e.g. <lnA>) depend on the analysis programs and techniques. For example, groups usually use not the total muon number (extrapolating data beyond the extent of their muon arrays, often) but a "truncated" muon number, not including muons within a certain radius of the shower axis. This minimizes the effects of punch-through energetic hadrons, which lie near the core. However different groups use different minimum radii; it would be useful to explore the extent to which the results depend on the value of this minimum.

Of course a major problem concerns the specific Monte Carlo model of the primary interaction, as noted above. The model uncertainty is reflected in the composition uncertainty. For example, models with a high average inelasticity, K, result in a greater muon production and earlier shower development for a given primary nucleus (e.g. proton) than models with low K. Thus a light (low <lnA>) composition with a high average value of K would result in observables similar to a heavier (higher <lnA>) composition and a low average K. Cesar Costa has referred to this as the "KAU" (inelasticity-average mass composition-uncertainty) problem [5]. The x distributions of the leading, final-state baryon in p-N interactions for various models (VENUS, QGSJet, etc.) is shown in Kampert's Hamburg ICRC paper [6]. It is reasonable to assume that these model uncertainties will be resolved by experimental data from the CERN Large Hadron Collider (LHC) in a few years. The desired data were discussed in the NEEDS Workshop at Karlsruhe in 2002 [7] and will be addressed again at the forthcoming Prague conference "From Colliders to Cosmic Rays" [8]. The primary point here is that groups comparing results by utilizing common analysis procedures should certainly use the same interaction models. Of course, given the uncertainty in interaction models, the results could be different. However, if all other uncertainties between different data sets are resolved, one may consider "tuning" the interaction models to bring the results (e.g. on <lnA> vs. E) into agreement. Although clearly less desirable than improving the models with direct accelerator data, this approach may be worth considering while awaiting completion of the LHC.

One interesting result relevant to composition studies is the GAMMA study of a selection of "young" EAS events, i.e. events with an age parameter less than a standard deviation below the mean. This selects a subset of events, which are probably mostly protons, and indeed this distribution shows a steeper spectrum, with an exponential index of –3.3, above the knee than the all-particle spectrum. The knee still occurs at about 3 PeV, and the slope at lower energies parallels the all-particle spectrum with a slope of about –2.7 [9]. It would be interesting to study also the spectrum of the oldest showers, which would correspondingly be most probably dominated by Fe primaries. This spectrum would be expected to not have a knee except perhaps at a much higher energy. A similar analysis could be done by selecting events with anomalously low and high accompanying muon numbers in each energy bin, or perhaps by the combinations: selecting young showers with low muon numbers, and old showers with high muon numbers.

4. Conclusions

Contemporary communications and computation technologies make the sharing of data and of analysis procedures much more practical than might have been the case some years ago. It would certainly be very interesting to see two very different data sets, from arrays at very different elevations, for example, analyzed with two different analysis procedures (as adopted by the two different collaborations), but resulting then in four sets of results on primary spectra and energy-dependent composition. Hopefully, such studies will assist the community in converging on a spectrum and composition on which all experts can agree and which can then be shared with the global particle astrophysics community as the "final word".

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