DETERMINING COSMIC RAY MASS COMPOSITION FROM EXTENSIVE AIR SHOWERS

Physics, Procedures, and Problems

Gerd Schatz
Habichtweg 4, D-76646 Bruchsal, Germany

May 17, 1999

It is now generally accepted that the bulk of cosmic rays are accelerated at discrete sites in our Galaxy and roam around for tens of million years before incidentally hitting the Earth. Since they are overwhelmingly charged particles they are deflected by the interstellar magnetic fields and have lost all memory of their origin when they eventually arrive. This implies that their direction of incidence on the Earth is no more related in any way to their origin. Hence the only quantities which can give us at least circumstantial information about their origin are energy distribution and composition. Therefore the determination of primary cosmic ray composition constitutes a crucial problem in cosmic ray origin.

Up to energies of about a few hundred TeV charge and mass of the primary particle can be determined with complex detector systems flown on balloons at the upper end of the atmosphere or on satellites. The flux of cosmic rays decreases steeply with energy, though. The weight and space limitations on balloons and satellites therefore prevent the extension of such measurements to higher energies. Hence the only way to study cosmic rays at higher energies is by ground based measurements of **extensive air showers (EAS)** which develop in the atmosphere when a high energy particle hits the Earth. This amounts to the attempt to identify the primary particle via measurements behind an absorber of c. 1 kg/cm^2. Experiments with this aim have been performed since decades. Fig. 2 shows a compilation of results [1]. Here the hatched band at lower energies represents a summary of direct (i. e. balloon and satellite) measurements. In the EAS range above c. $10^5 GeV$ the scatter is dramatic and one has to conclude that the field is in a mess.

In the following paragraphs I will discuss some important **properties of EAS** in detail based on simulations with the CORSIKA program [2]. Such simulations should be taken with a grain of salt as will be extended later in this paper. Before going into details I should make an important comment: Each primary cosmic ray particle is completely characterized by 8 quantities which can be divided into two groups (cf. fig. 3): its direction, position, arrival time (5 numbers altogether) and its energy, mass and charge. When these 8 numbers have been measured one has obtained complete information about the primary. The first 5 quantities can be measured independently, at least to reasonable accuracy. Unfortunately they are of almost no astrophysical significance because the charged cosmic ray particles appear to be homogeneous in space and time. (The only exception is a small directional anisotropy with respect to celestial coordinates which is of order 10^{-3} and will be neglected in the following discussion.) The latter group of three may be called intrinsic properties. Their determination is the aim of many experiments. Nobody has ever proposed a feasible method of determining the charge of the primary from EAS measurements, and the determination of energy and mass are thoroughly entangled. (It is nevertheless customary to talk of elements, i. e. nuclear charge, when discussing composition although EAS observables are in fact sensitive to the primary mass number. It is tacitly assumed that the isotopic composition of the elements in cosmic rays is the same as on earth. In view of observational (in)accuracies this is a reasonable assumption.)

An EAS is conceptionally very simple (cf. figs. 4 and 5): A high energy particle enters the atmosphere, collides with an air nucleus and produces a (usually large) number of secondary particles most of which go on and do the same. In this way the energy of the primary is quickly fragmented and the number of particles in the shower increases exponentially. Eventually some shower particles drop below the detection threshold. Then the increase of the number of particles levels off and turns around. Simultaneously there is a flow of energy from hadrons (which are the primaries) to electromagnetic particles, mainly via the decay of neutral pions, and to muons and neutrinos, mainly via the decay of charged pions, with essentially no backflow of energy to the hadron component. The particles arriving at observation level form a flat disc with a width of order meters and a diameter of several hundred meters (fig. 6).

The development of an EAS in the atmosphere is modelled using Monte Carlo methods. Most observables depend on energy and mass of the primary but in different ways. Thus it is possible, in principle, to determine these two quantities when at least two independent observables are measured and compared to the simulations. (The pitfalls of this procedure will be discussed below.) As an example, figs. 7 and 8 (from ref [3]) show the longitudinal development of the electron number in EAS initiated by protons and iron nuclei, respectively, at two primary energies, 10^{14} and $10^{15} eV$. The curves are mean values of 500 showers each, and different curves in each group represent calculations with different assumptions about the high energy interactions between hadrons and air nuclei. One standard observable of EAS measurements is the electron number on observation level, i. e. at fixed atmospheric depth. It can easily be seen by comparing the two figures that this number depends on primary energy as well as on mass although the sensitivity to mass is much smaller than to energy. It is also obvious from figs. 7 and 8 that the showers reach their maximum at smaller atmospheric depth if the primary is an iron nucleus as compared to a proton of the same energy. So by measuring electron number and depth of maximum one can determine both mass and energy of the primary. An example of such an experiment will be described below. A more common second observable, in addition to and independent of electron number, is the number of muons in the shower. The corresponding simulations are shown in figs. 9 and 10 [3]. The figures display the distributions of muon and electron numbers on sea level for the same showers as in figs. 7 and 8. The potato like curves indicate the range of fluctuations, and different curves of each group again refer to different interaction models. The lateral extent of muons in EAS has a diameter of several hundred meters, therefore the total muon number has probably never been determined experimentally in any EAS. A more realistic quantity, displayed in fig. 10, is the number of muons in a limited radial range (called 'truncated muon number' by the KASCADE collaboration). An experimental example of such a measured two-dimensional distribution from the KASCADE experiment is shown in fig. 11. This result will be discussed in the contribution by K. H. Kampert [5] to this workshop.

If the procedures are so straightforward why do the various experiments disagree as much as demonstrated in fig. 2? The main **problems** are
insensitivities
fluctuations
insufficient knowledge of high energy hadronic interactions and
- limited statistics
which will now be discussed successively.

The HEGRA group have combined the measurements of electron number and the height of the shower maximum to determine primary energy and mass simultatenously. The latter can be derived from the measurement of the lateral distribution of the Cherenkov light emitted by fast electrons in the atmosphere. The principle of the method is displayed in fig. 12. Here the hatched band represents the electron number at various depths in the atmosphere (not the lateral extent of the electron cloud!). Although the refractive index of air is very close to 1 some of the electrons move faster than light at their respective depth and hence emit Cherenkov radiation into a narrow cone whose opening angle varies with height. It is obvious from fig. 12 that the lateral distribution of Cherenkov light depends on the distance between shower maximum and observation level. By this way it is possible to measure the height of shower maximum for each individual shower. The HEGRA collaboration have exploited this feature with their AIROBICC system of open photomultipliers [6] and a more detailed description of the procedure has been given by Lindner [4]. Their result is shown in fig. 13 which displays the distribution of shower maxima for a certain interval of primary energies. The histogram with error bars represents the experimental result, the two broken curves the simulated distributions for primary protons (right) and iron nuclei. The latter were approximated by Gaussians. One has to bear in mind, of course, that the real mass distribution will contain further components. Fig. 13 reveals one of the main problems: The experimental distribution displays hardly any structure and it has to be decomposed into contributions which are equally structureless and, in addition, overlap considerably. The relative contributions of the various theoretical components are therefore extremely sensitive to small shifts of the experimental data or simulated distributions. This holds especially for the mass components in between the highest and lowest values; the latter are much better constrained by the wings of the measured distribution. Unfortunately, the situation is very similar for all other combinations of observables which have been used so far to determine mass composition of cosmic rays from EAS. For the combination of electron and muon numbers this will be demonstrated in the contribution on the results of the KASCADE experiment to this workshop [5].

Figs. 7 and 8 showed the *average* longitudinal development of the electron numbers in showers initiated by protons and iron nuclei. Individual showers deviate from this average more or less. The **fluctuations** around the mean are not terribly large for iron induced showers, as demonstrated in fig. 15 for 50 individual simulated events. For proton primaries, though, the fluctuations are dramatically larger as shown in fig. 16. Part of these fluctuations is due to the scatter of the height of the first interaction which amounts to about 70 to 80 g/cm^2. But this does in no way account for all, as demonstrated in fig. 17. Here the individual showers have been shifted horizontally to superimpose the depth of first interaction at $100g/cm^2$. It is obvious from fig.17 that a considerable fluctuation remains, due to the statistics of energy loss and particle production in hadron-air interactions. Closer inspection of fig. 16 reveals that the distribution of the electron number on sea level is asymmetric with a tail towards high values. This has some unfavourable consequences owing to the steeply falling spectrum because it implies that a small fraction of low energy primaries (where the intensity is large) may mimick primaries of much higher energy. (The situation is more favourable at sites a few thousand meters above sea level.). How large the fluctuations of proton induced EAS actually are is demonstrated by fig. 18. Here I show the 5 smallest and the 9 largest showers on sea level out of a sample 500 simulated events. While the small showers are not conspicuous except by their size the large showers divide into two groups: 6 showers simply develop late, one of them penetrates almost half the atmosphere before interacting. The remaining three exhibit a double-humped longitudinal distribution. Closer inspection (by D. Heck) revealed that the first interaction in these cases was diffractive and the leading particle, in all cases a baryon, travelled a considerable distance before interacting a second time. These examples show that one may expect very unusual events among proton induced showers at the level of a percent.

A shower initiated by a nucleus of mass number A and energy E can, to a first approximation, be considered the superposition of A showers initiated by protons of energy E/A because the binding energy of the nuclei involved are negligible as compared to the energy available in the centre of mass system. Hence fluctuations average out to a considerable extent [7] for showers induced by nuclei.

Figs. 19 and 20 show the longitudinal development of the number of muons in showers initiated by iron nuclei and protons, respectively. Again the fluctuations among proton induced showers are clearly larger.

All EAS simulation programs require input for the calculation of **collisions** between hadrons and air nuclei **at the highest energies**. Unfortunately, our knowledge in this field is incomplete with respect to energy and angular range. The FERMILAB collider, the highest energy installation available today, reaches an equivalent laboratory energy of c. 2 PeV, and the LHC presently under construction at CERN will extend this to 100 PeV. This covers a substantial part of the EAS region. This does not hold, unfortunately, for the angular range. Collider detectors do not cover the direct forward region. Particles emitted into the forward cone take the bulk of the primary energy which determines the development of the air shower. This problem is illustrated by fig. 21 which shows the rapidity distributions of secondary particles in proton antiproton collisions calculated with an interaction model used in EAS simulations. The upper part gives the number distributions. The different curves are labelled with the equivalent laboratory energy. The two vertical bands limit the acceptance of two collider detectors. One of these, CDF, operates at the FERMILAB collider, i. e. at the highest energy available today, the other is the one with largest rapidity range achieved so far among high energy experiments. One realizes that the detectors register a large fraction of the secondary particles. The lower part of fig.21 displays the rapidity distribution of energy after the collision. It is obvious that only a small fraction of the primary energy is measured by these detectors, the smaller, the higher the primary energy. Since it is this energy which governs the EAS development collider experiments do not yield (in fact, aim at) the most important information required for modelling EASs. With a bit of exaggeration, but really not very much, one may conclude that the higher the energy of a collider, the less important are its results for cosmic ray physics. In this situation one has to rely on 'intelligent' extrapolation of low energy results guided by phenomelogical theory. Various attempts have been made along these lines and advanced simulation programs such as CORSIKA [2] offer a number of such interaction models. As can be seen from figs. 7 to 10, e.g., they usually do not differ drastically in their predictions. But one has to bear in mind that the sensitivity of observables to primary energy and mass is not large. Hence small differences between simulation results can produce considerable differencs in derived mass composition.

A further impediment is the limited **statistics**, not usually of experimental data but of simulated events whose number is frequently much smaller than that of observed ones. This again matters because of the high sensitivity of the results to small shifts in experimental or simulated distributions.

Is there any **chance to make progress** in view of these obstacles? The large intrinsic fluctuations of EAS observables cannot be influenced except, to a limited extent, by the choice of the observation height. While one may hope that somebody finds a set of observables more sensitive to primary mass than the ones exploited so far this is at least uncertain. The statistics of measurement and simulations can be expected to improve steadily, the latter in view of the still increasing computer capabilities. One stumbling block where unfortunately prospects are dim is particle production at high energies in the forward region. This is not so much a question of technical possibilities but of priorities since experiments in this direction have been proposed (and started although on a too restricted scale [9]) [8]. To the best of my knowledge there are no plans to perform such experiments at one of the big colliders in the foreseeable future. Hence we are in a situation of which a German proverb says we have to 'pull ourselves out of the swamp by our own hair'[1]. The sad experience that the same set of experimental data can yield different results when evaluated with different interaction models demonstrates that EAS observables are sensitive to details of high energy interactions. Hence these models can be constrained if more than the minimum number of two quantities are measured of each shower. This is the approach of the KASCADE experiment [10] a ground plan of which is shown in fig. 22. The experiment consists of an array of 252 detector stations, a central detector and a muon tunnel (still in the installation phase). It allows to measure all three components of each individual EAS, muons, hadrons, and electromagnetic particles as well as their lateral distributions. Details of the experiment and some results are given elsewhere [5, 11]. The more observables of each shower are determined the more there is a chance to constrain interaction models. As the contribution by K. H. Kampert [5] shows this is more than a pious hope. The other approach which may and, in my opinion, should be taken is to combine the large amount of experimental information available and to try to evaluate it in a homogeous way. In the past, different groups frequently used different simulation programs to analyse their data. This made comparison of experiments difficult. Fortunately some progress has been made in that respect over the last years since CORSIKA [2] has become a kind of reference program used by many groups. Such a 'unified' approach should include of course emulsion data which not only use a very different technique but register very different aspects of EAS due to their high observation level and threshold. This implies that the particles which they register are much closer to the first interaction than other EAS observables. Some of their results indicate that the very forward region is not described correctly by any of the current interaction models [12, 13]. In my opinion there is a fair chance to obtain information about particles emitted into the forward region in high energy collisions from cosmic ray experiments before particle physicists at colliders have deigned to study this region with their facilities.

[1]This expression is based on a story by Baron Karl Friedrich Hieronymus von Münchhausen (1720 - 1797) who, as a young man, served as officer in the Russian army fighting the Turks. Later in his life he retired to his family estate at Bodenwerder in northwest Germany where he entertained the local gentry with stories of his Russian adventures. These appeared somewhat improbable which earned him the nickname of 'the lying baron'. In one of his stories he describes how he got into a swamp on his horse and started to sink down. He saved himself by firmly gripping at his hair and pulling himself up. By clinging his legs firmly around the body of his horse he was even able to pull it out together with himself.

Acknowledgements

I thank my colleagues of the KASCADE collaboration for many discussions which contributed to my understanding of the problems described in this paper. Special thanks are due to D. Heck for providing me with simulation data, A. Haungs and M. Roth for their patient instructions concerning LATEX and PAW, and D. Heck, J. Hörandel, D. Horns (of the HEGRA collaboration), J. Knapp, and M. Risse for providing some of the figures. Most of all I thank the organizers of this workshop for their invitation and financial support.

References

[1] J. Hörandel, PhD Thesis, Karlsruhe University, 1997; FZKA 6015, (1997)

[2] D. Heck, J. Knapp, J. N. Capdevielle, G. Schatz, T. Thouw, FZKA 6019 (1998)

[3] J. Knapp, D. Heck, G. Schatz, FZKA 5828 (1996)

[4] A. Lindner, Astropart. Phys. **8** (1998) 235

[5] K. H. Kampert, *Tests of interaction models and cosmic ray composition measurements by KASCADE*, these proceedings

[6] A. Karle et al. (HEGRA collaboration) Astropart. Phys. **3** (1995) 321

[7] G. Schatz, T. Thouw, K. Werner, J. Oehlschläger, K. Bekk, J. Phys. G: Nucl. Part. Phys. **20** (1994) 1267

[8] K. Eggert and C. Taylor, Nucl. Phys. B (Proc. Suppl.) **52B** (1997) 279

[9] L. W. Jones et al. (MiniMax collaboration), Proceedings of the 24^{th} International Cosmic Ray Conference, Rome 1995, Vol. 1, p. 886

[10] H. O. Klages et al. (KASCADE collaboration), Nucl. Phys. B (Proc. Suppl.) **52B** (1997) 92

[11] A. Haungs, *Measurements of EAS muons with $E > 2$ GeV at the KASCADE experiment*, these proceedings

[12] A. Ohsawa, *Present status of Centauro events by emulsion chamber experiments at Mt. Chacaltaya*, these proceedings

[13] M. Tamada, *Extensive comparison of emulsion chamber data at high mountains with CORSIKA simulations*, these proceedings

[14] D. Horns, Verhandl. DPG (VI) **33** (1998) 25

Figure captions

Some of the figures are self-explaining, so captions are only given for part of the figures.

Fig. 2. Compilation of results on cosmic ray mass composition as expressed by the mean of ln A. The hatched band at low energies summarizes results by direct measurements. (From ref. [1])

Fig. 7. Average electron number versus atmospheric depth for simulated showers induced by vertical protons. The various curves represent results calculated with different interaction models. (From ref. [3])

Fig. 8. Ditto for iron nuclei.

Fig. 9. Distribution of the events displayed in figs. 7 and 8 in the $N_e - N_\mu$ plane. The 'potato shaped' curves indicate the range of fluctuations. (From ref. [3])

Fig. 10. The same as fig. 9 except that the number of muons in the radius range 40 to 100 m is displayed.

Fig. 11. Observed two-dimensional $N_e - N_\mu$ distribution measured by the KASCADE experiment.

Fig. 12. Schematic explanation of the production of Cherenkov light in EAS. The hatched band indicates the electron intensity at various atmospheric depths. The opening angle of the Cherenkov cone depends on electron energy and refractive index of the air both of which vary with height.

Fig. 13. Distribution of the heights of shower maximum as measured by the HEGRA collaboration (from [14]). The histogram represents the measurements, the two Gaussians represent simulations for primary protons (broad distribution) and iron nuclei.

Fig. 14. Illustration of the procedure of determining primary mass from the measurement of the electron number and Cherenkov light [4, 14].

Fig. 15. Longitudinal development of electron number in 50 individual showers induced by primary iron nuclei simulated with the CORSIKA program.

Fig. 16. Ditto for primary protons.

Fig. 17. The same showers as displayed in fig. 16 but shifted horizontally such that the first interaction occurs at the same depth of 100 g/cm^2.

Fig. 18. Longitudinal development of electron number for selected proton induced showers simulated with the CORSIKA program. The curves represent the 5 smallest and the 9 largest showers at sea level out of a sample of 500.

Fig. 19. Longitudinal development of muon number in 50 individual showers induced by primary iron nuclei. The curves were calculated with the CORSIKA program.

Fig. 20. Ditto for proton induced showers.

Fig. 21. Rapidity distributions of secondary particles in high energy proton-antiproton collisions. The upper part shows the number distributions, the lower ones the energy distributions. The curves are labelled with the equivalent energy in the rest system of one of the primary particles. The angular acceptance of two collider experiments is indicated by the vertical bands.

Fig. 22. Lay-out of the KASCADE experiment [10].