Studies of the mass composition of cosmic rays with the SPASE-2/VULCAN instrument at the South Pole

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Abstract

The electron, muon and air-Čerenkov components of air-showers have been studied simultaneously using the SPASE-2, AMANDA and VULCAN experiments at the South Pole. 32000 events observed by SPASE-2 and VULCAN pass all selection cuts. We report the results of our analysis for these events. The high energy (>500 GeV) muon content of a subset of these showers will be obtained using the AMANDA-B detector. The combination of muon and X_m information promises a powerful tool for mass composition studies.

1 Introduction

Above 10^{14} eV the mass composition of cosmic rays must be inferred indirectly from extensive air showers observed at the ground. Measurements of the electromagnetic, muon and Čerenkov components of showers can be used to deduce primary mass. A shower property closely linked to primary mass is the depth of maximum (X_m). Patterson and Hillas (1983) suggested that X_m and the slope of the Čerenkov lateral distribution (CLD) are strongly related. The slope may be quantified by a parameter κ, defined as ln $\frac{C(40)}{C(100)}$. C(r) is the intensity of Čerenkov light at radius r from the shower core. In addition it is found that the intensity of Čerenkov light beyond 100 m from the core is an indicator of primary energy (Paling et al. 1997).

A multi-component experiment comprising the SPASE-2/VULCAN and AMANDA instruments has been established at the South Pole. To interpret the data from this experiment a program of simulations has been undertaken. 50,000 events have been simulated using the MOCCA (Hillas 1995) - SIBYLL (Fletcher et al. 1994) code (including a model South Polar atmosphere) (Hinton 1998) and passed through further simulations of muon propagation in the ice (Lohmann et al. 1985) and the response of all three instruments (Hinton 1998). Fig. 1 shows the relationship between κ and X_m for a subset of these showers.

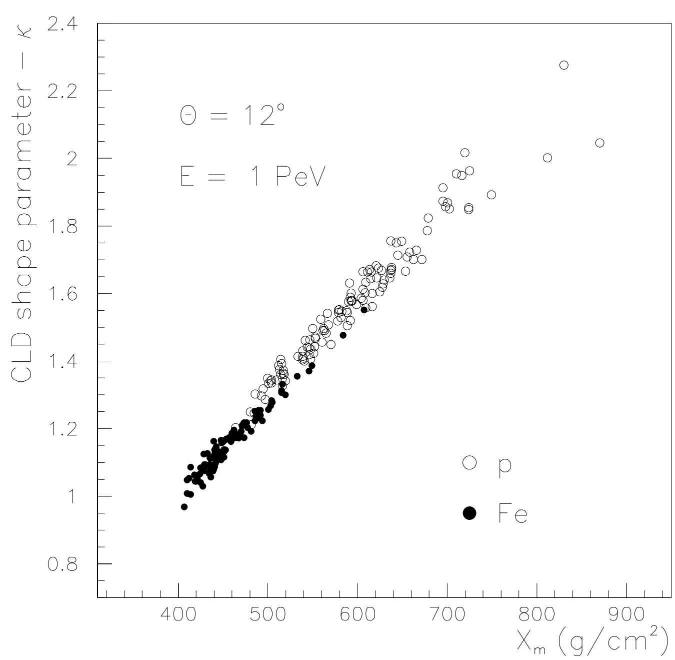

Figure 1: The relationship between κ and X_m for a subset of showers from MOCCA-SIBYLL simulations.

Using the full shower library (zenith angles 0-30 ° and 4 primary masses) we find $X_m = \frac{X_0}{\cos\theta} - (463 - 76\kappa - 97\kappa^2)$, where X_0 is the South Pole overburden of 688 g cm^{-2} and θ is the zenith angle. In addition it is found that primary energy may be estimated from the Čerenkov signal at 100 m from the shower core via: E(PeV) = $4.23 \times 10^{-4} \times C(100)^{0.91}$, where $C(100)$ is expressed in photoelectrons/m^2. This relationship has 15% mass dependence at 1 PeV.

The SPASE-2 and VULCAN instruments are described in Dickinson et al. 1997,1999a and 1999b. VULCAN comprises nine wide angle air-Čerenkov detectors operating in conjunction with the SPASE-2 scintillator array. VULCAN waveforms are digitised using custom-built Flash-ADCs. This allows accurate measurement of the night sky background on an event-by-event basis. The array is similar to but smaller than the AIROBICC (Karle et. al., 1995) and BLANCA (Cassidy et al. 1997) arrays.

2 Experimental data and simulations

The SPASE-2 scintillator array provides an event trigger with a threshold of ∼50 TeV for proton primaries. The SPASE-2 data are used to determine the shower core/direction to an rms accuracy of 4 m/1° at 1 PeV. The VULCAN data are used to measure the CLD.

After the rejection of data compromised by adverse weather conditions, snow accumulation on the detectors or strong auroral outbreaks, 8000/24000 events (1997/1998) pass all selection cuts. The principle cuts are: (i) the particle density at 30 metres from the core must be greater than 5 m^{-2} (equivalent to an energy of approximately 0.3 PeV for iron primaries and 0.15 PeV for protons), (ii) the shower core must be contained within the array and (iii) the shower direction reconstructed by SPASE-2 must be within 14° of the VULCAN pointing direction. The CLD is used to calculate X_m and E using the relationships given earlier. A correction (calculated from the detector simulation) is made to X_m to account for systematic measurement errors. This correction has the value of a ∼20 g cm^{-2} decrease at 1 PeV and a ∼ 10 g cm^{-2} increase at 10 PeV. The mass dependence of this correction is ∼5 g cm^{-2} at 1 PeV, increasing at lower energies. Data from 1997 and 1998 have been compared in an attempt to understand systematic errors. The 1997 and 1998 data differ in angle of inclination of the VULCAN detectors (23° and 12.5° , to align with the AMANDA-A and B detectors respectively) and in the relative gains of the VULCAN detectors. The derived X_m differ by $\lesssim$5 g cm^{-2}. Fig. 2 shows both sets plotted alongside the combined set. The dominant source of systematic error in X_m is the choice of interaction model. As an illustration there is a ∼10 g cm^{-2} increase in X_m from MOCCA/MOCCA to MOCCA/SIBYLL.

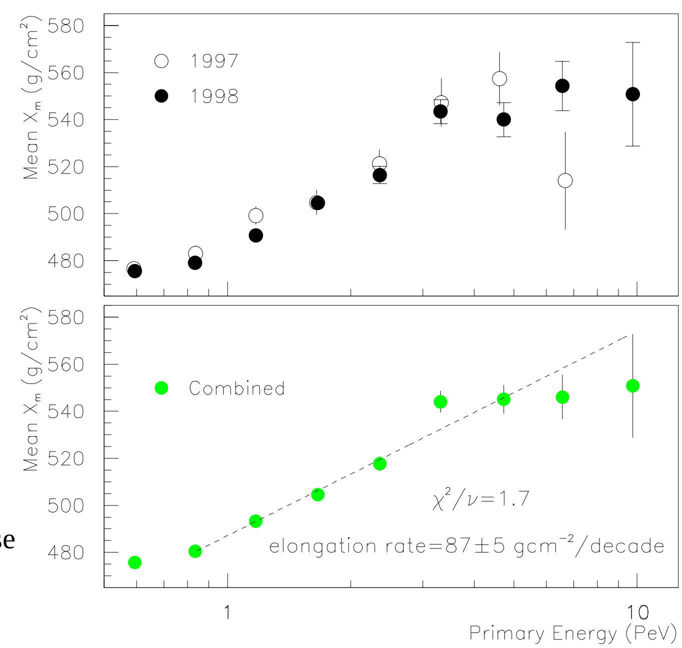

Figure 2: A comparison of X_m vs E for the 1997 and 1998 SPASE-2/VULCAN data.

3 Depth of Shower Maximum

Fig. 3 shows the mean depth of shower maximum, derived jointly from the 1997 and 1998 VULCAN data together with data from CACTI (Paling et al. 1997), DICE (Boothby et al. 1997) and HEGRA (Arqueros et al. 1999) are shown for comparison. From the four sets of HEGRA data in (Arqueros et al. 1999) we have used those obtained with the energy computed assuming proton primaries and using Čerenkov light measurements.

At 1 PeV all experiments agree to within ∼25 g cm^{-2}. The simulations used to obtain X_m differ between the four experiments (CACTI data are calculated using MOCCA/MOCCA, HEGRA using CORSIKA/QGSJET and DICE using CORSIKA/VENUS). Reanalysis of the CACTI data using MOCCA/SIBYLL would result in a ∼10 g cm^{-2} increase in X_m at 1 PeV, greatly improving the agreement with other experiments. At 10 PeV the DICE result has a much larger (>50 g cm^{-2}) mean X_m than other experiments.

A fit over the full energy range (excluding the first point which is subject to greater systematic errors) of the SPASE-2/VULCAN data (0.7-10 PeV) results in an elongation rate of 87±5 g cm^{-2}/decade but with a χ^2/ν of 1.7 (see Fig. 2). This represents a 10% probability of consistency with a constant elongation rate. A value of 78.3±1.9 (stat) ±6.2 (syst) g cm^{-2}/decade (in the energy range 0.3-10 PeV) has been derived from the HEGRA data (Arqueros et al. 1999). It is intriguing that the last four SPASE-2/VULCAN points have a very small elongation rate (8±28 g cm^{-2}/decade) as have the last three points in the HEGRA data.

Fig. 4 shows the width of the X_m distribution as a function of energy. The intrinsic spread in X_m is estimated by quadrature subtraction of the measurement error from the observed spread (this method is approximate because of the non-gaussian tail of the X_m distribution). The SPASE-2/VULCAN and HEGRA (Cortina et al. 1997) data are consistent within the uncertainty in the SPASE-2/VULCAN measurement error (~ 5 g cm^{-2}). The DICE data are not consistent below 5 PeV. The SPASE-2/VULCAN data suggest that the rms spread in X_m decreases by 11 ± 3 g cm^{-2}/decade between 0.5 and 10 PeV.

4 High Energy Muons

Conclusions drawn with respect to mass composition must be considered in the light of the model dependency of our method. Several event generators, including SIBYLL, were compared by the Karlsruhe group. (Knapp et al. 1996). SIBYLL was found to produce relatively few GeV muons compared to other event generators. At the relevant energy of 1 PeV, X_m calculated by QGSJET is ∼30 g cm^{-2} less than SIBYLL. Hence the proton and Fe lines in Fig. 3 are moved down by this amount.

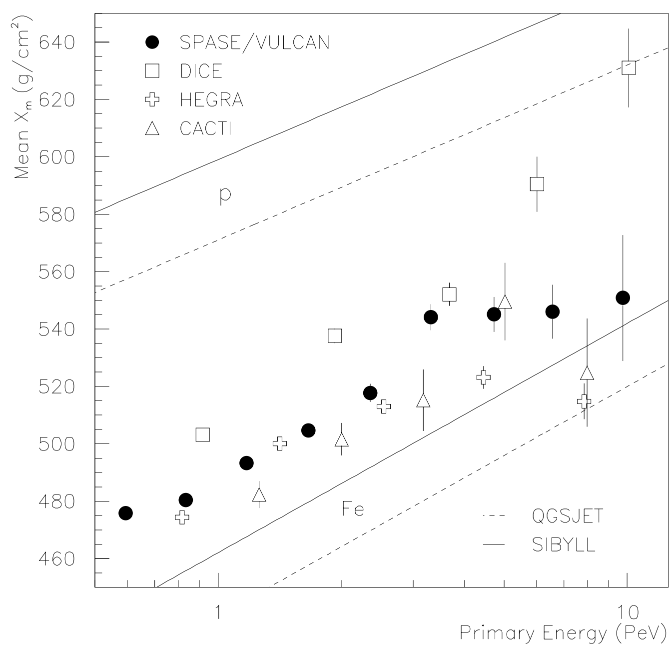

Figure 3: The depth of maximum measured by SPASE-2/VULCAN compared to other experimental results and the MOCCA/SIBYLL and QGSJET models.

High energy muons are produced early in the development of the shower and contain more direct information on primary mass than the lower energy muon component (Gaisser, 1990). According to Knapp et al.(1996) the difference in the number of (> 1 TeV) muons at primary energy 1 PeV is a factor ∼2 between iron and protons. For >1 GeV muons this is reduced to a factor 1.5. The difference between the five studied event generators at 1 PeV primary energy is ± 15% for the number of muons of >1 TeV and ∼60% for the number >1 GeV. For >1 TeV muons there is a factor 1.75 difference in the integrated muon energy between 1 PeV proton and iron primaries. At 3 PeV this factor has increased to 2.5 (MOCCA/SIBYLL).

The limitations of a two-component approach to analysis of air showers is apparent. Interpretation is model dependent and results are difficult to compare between groups using different simulations. SPASE-2 and VULCAN measure air showers in coincidence with high energy muon (>500 GeV) data from AMANDA. The possibility of measuring the total muon energy using AMANDA-B is being studied.

5 Conclusions

The data presented here represent a first step towards a mass composition measurement with the SPASE-2/VULCAN/AMANDA coincidence experiment. 32,000 SPASE-2/VULCAN events above 0.5 PeV have been analysed and the depth of shower maximum extracted on an event-by-event basis. The results of this analysis are broadly consistent with other experimental results in this energy range. Work is underway to improve our understanding of systematic effects on the data. 5% of these showers were also detected in the AMANDA-B detector and analysis is in progress to extract the total muon energy from these events. The addition of the muon data will decrease the dependence of the inferred mass on models. In addition we hope to constrain the choice of interaction model in this region.

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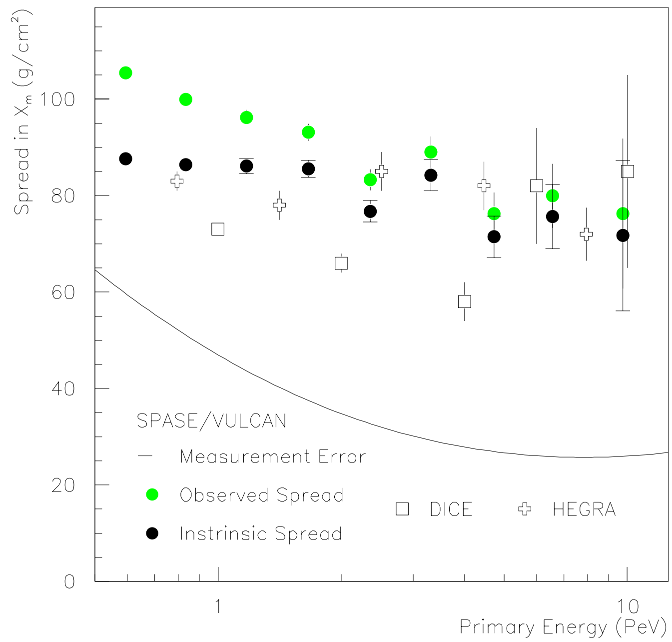

Figure 4: The rms spread in X_m as a function of energy. Other results are shown for comparison.

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