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Cosmic Ray Astrophysics in the Knee Region and Implications for Gamma Ray Astronomy

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Abstract.

Following the discovery of ultra high energy cosmic rays with energies of PeV and higher in the 1950's and detailed studies on the energy spectrum in the TeV-PeV-EeV regions in 1960's, there has been enormous interest in learning about the nature of astrophysical sources capable of accelerating particles to these extremely high energies and about their propagation in the interstellar and intergalactic space. Direct observational studies on cosmic ray sources through detection of PeV energy γ-rays have yielded very scanty information due to the absence of steady sources above the presently detectable flux limits. Therefore, indirect information on the nature of cosmic ray sources and acceleration processes has to be obtained from measurements on the energy spectra of various nuclear groups. In this context, the presence of the 'knee' at $E \sim 3 \times 10^{15}$ eV is very significant and it is important to obtain accurate information on the chemical composition of cosmic ray flux around the 'knee' to understand the nature of cosmic ray sources contributing to this part of the energy spectrum. We summarise here the present status of UHE γ-ray astronomy and review some of the recent experimental results on energy spectra and composition.

Keywords : – Cosmic ray spectrum and composition – γ-ray astronomy

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1. Introduction

The presence of ultra-high energy particles in cosmic radiation was demonstrated conclusively by Pierre Auger (Auger 1939) in late 1930's through detection of large showers. Several studies (e.g., Clark et al 1961 and Linsley 1963) were able to establish the continuation of the power-law shape of the energy spectrum to extremely high energies. The flux of cosmic ray particles covers a range of almost 30 decades from about 1 particle/(cm^2 sr s) at 100 MeV to about 1 particle/(km^2 sr century) at energy $\sim 10^{20}$ eV. Observation of two structures in the spectrum, the 'knee' at $\sim 3 \times 10^{15}$ eV where the spectral exponent changes from about -2.7 to -3.1 and the 'ankle' at $\sim 10^{18}$ eV where the spectrum seems to become flatter again, has generated a lot of interest among astro-particle physicists.

Although considerable progress has been made in understanding the details of various possible acceleration processes and the energetics of possible sources, the origin of high energy cosmic rays still remains an unsolved problem. In view of the fact that any specific source and acceleration model can not account for the entire observed energy range, it is generally agreed that a wide variety of sources must be contributing to the observed spectrum. However, there must be a generic relationship between the processes occurring at these sources to assure the continuity and smoothness of the spectrum over such a broad energy range and to avoid any scenario of cosmic conspiracy. Most discussed mechanism for accelerating particles upto energies $\sim 10^{15}$ eV is diffusive shock acceleration caused by supernova explosion which was first proposed in its basic form by Fermi (1949). Propagation of SN shocks into the stellar wind of the progenitor star has been shown (Biermann 1993) to extend the energy spectrum of accelerated particles and nuclei to energies as high as $\sim 10^{17}$ eV.

The propagation of cosmic rays through the environment of their sources and in interstellar space is another important aspect which has strong influence on the observed characteristics of cosmic ray flux near the Earth. For example, it has been argued that the 'knee' is the consequence of the increasing inability of the $\sim \mu$G magnetic field in the galactic disk to keep the particles trapped within the disk. On the other hand, Erlykin and Wolfendale (1998) have proposed the 'single source' model where the structure of the knee including the changes in the chemical composition of the flux around the knee is sought to be explained as due to acceleration of particles by a single nearby and relatively recent supernova.

Most of our knowledge about the universe has been obtained through study of photons and recent studies in X-ray and γ-ray bands have added very significantly to our understanding. However, attempts to study and understand the sources of cosmic rays have not met similar success due to the fact that charged particles, unlike photons, are scattered by the magnetic fields permeating the interstellar space. A charged particle is detected on Earth with arrival direction which has almost no relation to the direction it acquired after acceleration near the source, except possibly for particles of energies $> 10^{19}$ eV. Therefore early suggestions for detection of cosmic ray sources through γ-rays produced through decays of neutral pions produced in hadronic interactions (Morrison 1958, Cocconi 1960) between high energy particles and matter around the sources were pursued with great vigour, particularly at TeV energies through observations on atmospheric Cherenkov radiation (Chudakov et al 1963). Attempts were also made to detect γ-rays of energies $\sim 10^{14-15}$ eV with air shower arrays using the *μ-poor* criterion (Hayashida et al 1981, Dzikowski et al 1983 and Kirov et al 1985). This field of ultra-high energy (PeV) γ-ray astronomy received a boost with the announcement (Samorsky and Stamm 1983) of detection of a 4.8h modulated signal at $\sim 10^{15}$ eV from the binary X-ray source, Cygnus X-3 (Cyg X-3). However, despite enormous efforts worldwide (Ong 1998), success similar to that achieved in other wave-bands like X-rays and high energy (30-1000 MeV) γ-rays could not be repeated at PeV energies. On the other hand, the field of very high energy (TeV) γ-ray astronomy has been able to achieve significant success, thanks to the development of the imaging technique by the Whipple collaboration (Weekes et al 1989) and detection of the 'standard' candle' (Crab nebula) as well as 'flickering' sources (Mkn 421 and Mkn 501) by several groups (Lorenz 2001).

Direct studies on γ-ray sources at PeV energies, if detected, would provide very valuable information on temporal and spectral features of emissions from specific sources. However this knowledge can only complement information to be obtained from detailed studies on the fine structure of the energy spectrum, particularly around the 'knee', and the chemical composition of particle flux as a function of energy. This information is crucial for achieving a satisfactory understanding of the nature of sources and the dominant processes for acceleration of particles, at least upto $\sim 10^{16}$ eV.

Therefore, in this presentation, we first review the present status of the field of PeV γ-ray astronomy and then discuss the on-going experimental efforts to improve on the quality and accuracy of results on energy spectrum and composition of primary flux at energies $\sim 10^{14-16}$ eV.

2. Ultra High Energy (PeV) γ-ray Astronomy

Early attempts to detect γ-ray sources at PeV energies with air shower arrays did not yield encouraging results due to poor angular resolution of the arrays, requiring search for excess over angular bins of large size ($10^o \times 10^o$ and larger). The μ-poor criterion was also not very effective for rejection of the large background of showers initiated by charged primaries due to relatively very small area of muon detectors. Therefore, observation of an excess in a small angular bin around Cyg X-3 by the Kiel group (Samorsky and Stamm 1983) was considered to be a success due to the improvement in the angular resolution of the Kiel array. Soon thereafter, several groups (Lloyd-Evans et al 1983, Morello et al 1983, Kifune et al 1985, Lambert et al 1985, Tonwar et al 1985, Watson 1985) with similarly improved angular resolution also reported positive detection of Cyg X-3, though mostly with poor statistics. Unfortunately, several large arrays (Ong, 1998), which became operational in late 1980's and early 90's and which were specially designed to achieve good angular resolution and higher sensitivity for detection of showers due to γ-ray primaries have yielded negative results for Cyg X-3. However, it is interesting to note that the time-averaged flux measured by Samorski and Stamm (1983) during 1976-79 was as high as 7.4×10^{-14} photons cm^{-2} s^{-1} for $E \geq 2 \times 10^{15}$ eV as compared to the 95% CL upper limit of $5.2 \times 10^{-17} cm^{-2} s^{-1}$ for $E \geq 1.2 \times 10^{15}$ eV given by the CASA-MIA group (Borione et al 1997) from observations during 1990-95. In retrospect, the scenario proposed by Bhat et al (1986) seems even more plausible now where they suggested that Cyg X-3 was in an unusual active state at TeV-PeV energies during 1970's but its flux decreased with time exponentially with time constant $\sim$ 2 years. In fact, it has been suggested (Tonwar et al 1992) that almost all positive detections (Alexeenko et al 1987, Baltrusaitis et al 1987, Dingus et al 1988a and Tonwar et al 1988) during 1985-86 were essentially episodic Dingus et al 1988a and Tonwar et al 1988) lasting for only a few weeks at a time with the most active period being around April-May 1986. These observations also included the detection of short-duration bursts during June 1985. Since late 1986 there have been no statistically significant detections.

The results of observations on the other prominent X-ray binary, Hercules X-1 (Her X-1) have been even more dramatic. This interesting source was detected only as a short-duration episodic source during 1984-86, a few times at TeV energies and a few times at PeV energies. Surprisingly, the flux observed during episodes detected at different times during 1986, by Resvanis et al (1988) and Lamb et al (1988) at TeV energies and Dingus et al (1988b) and Gupta et al (1990) at PeV energies showed a very intriguing feature, namely, pulsations at a slightly ($\sim$ 0.16%) blue-shifted freequency compared to the well-known X-ray period of 1.24 s. Unfortunately, the largest episode observed in April 1986 by the Pachmarhi group (Vishwanath et al 1989) could not be phase-analysed due to some technical problems. Further, the Ooty group (Gupta et al 1990) reported detection of 5 episodes during July-December 1986 which were apparently phase-locked not only at the same blue-shifted pulsar period but also at phase of 0.65 for the 1.7d orbital period. However, no episodic emission has been observed by much larger and more sensitive experiments (Ong 1998) since 1987. For example, the episodic flux measured by Gupta et al (1990) in 1986 was as high as $3 \times 10^{-11} cm^{-2} s^{-1}$ for $E \geq 10^{14}$ compared to the 95% CL upper limit of $2 \times 10^{-13} cm^{-2} s^{-1}$ for $E \geq 1.15 \times 10^{14}$ on daily flux given by CASA-MIA collaboration (Borione et al 1997). Exploiting the advantage of the high altitude (4300 m, 606 g cm^{-2}), the Tibet ASγ collaboration (Amenomori et al 1992) has been able to put a stringent limit of $5.8 \times 10^{-13} cm^{-2} s^{-1}$ for $E \geq 10^{13}$ eV on the steady flux from Her X-1 from their observations during 1990-92.

The only other binary X-ray source which has been observed by 2 or more groups around the same time is Scorpius X-1 (Sco X-1) in the southern sky. Ooty group (Tonwar et al 1991) observed an episodic excess from the direction of Sco X-1 during March-April 1986 which was confirmed by Meyhandan et al (1993) with data from the Buckland Park air shower array. The episodic flux was estimated to be $6 \times 10^{-12} cm^{-2} s^{-1}$ for $E \geq 2.5 \times 10^{14}$ eV corresponding to the UHE gamma ray luminosity of 2×10^{35} ergs s^{-1}.

Apart from these three X-ray binaries, no other source was detected at PeV energies by more than one group around the same time during 1980's. Even these three sources have not been detected by the new, larger and more sensitive arrays such as CYGNUS (Alexandreas et al 1993), EAS-TOP (Ghia et al 1995), HEGRA (Willmer et al 1995), CASA-MIA (Borione et al 1997) and Tibet ASγ (Amenomori et al 1992) during 1990's. A realistic assessment of this situation, taking into account statistical significance of various detections during 1980's, leads to the conclusion that while a few may have been due to statistical fluctuations, most were genuine detections of sources which are transient in nature. During 1980's invocation of variability to account for non-detection of a suspected source was looked with suspicion but that perception has dramatically changed with observations on the Markarian sources during 1990's at TeV energies. Kerrick et al (1995) have reported observations on flaring from Mkn 421 with flux changing by almost an order of magnitude on the time scale of a few days in May 1994. Similarly, Buckley et al (1996) have observed significant variations on time scale of less than a day for Mkn 421 in 1995. Rapid flaring at TeV energies has also been seen for Mkn 501 by several groups, e.g. CAT (A. Barrau et al 1997), Telescope Array (Aiso et al 1997) and TACTIC (Bhat et al 1997, Bhatt et al 1999). Due to the source being in very active phase during 1997, Mkn 501 was also detected at multi-TeV with MILAGRITO water Cherenkov detector (Atkins et al 1999) and the air shower array at Tibet (Amenomori et al 2000a).

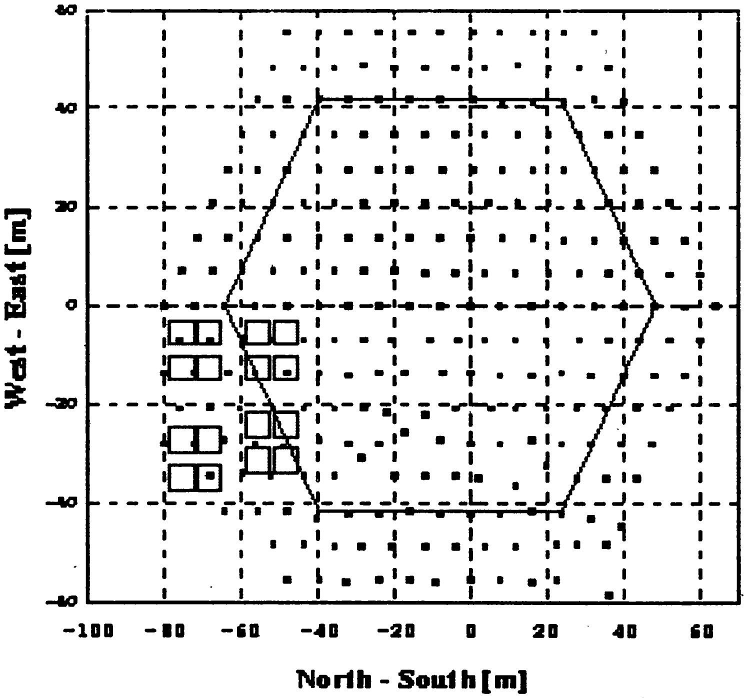

Figure 1. Schematic layout of detectors for the 217-electron detector GRAPES-III shower array at Ooty. 16 modules of muon detectors ($E_\mu \geq 1$ GeV) give a total effective detector area of 560 m^2 for efficient detection of μ-poor showers of primary energy $\sim$ 100 TeV (Hayashi et al 2001).

These observations strongly suggest that TeV-PeV sources, other than supernova remnants such as Crab and Vela, are more likely to be transient and highly variable with time. It is therefore necessary to have at least a few large and sensitive arrays operational around the world to be able to detect and study γ-ray emission at ultra-high energies. With this perspective, the GRAPES collaboration is operating two arrays at Ooty ($11^o.4$ N, $76^o.7$ E, 2200m) in southern India round the clock, the 100-detector GRAPES-II array (Tonwar et al 1995) with a 200 m^2 area muon detector and the 217-detector GRAPES-III array (Ito et al 1997) with a 560 m^2 area muon detector. The two arrays, separated by about 10 km, are completely independent. The very large areas of muon detectors with the two arrays are meant to identify the γ-ray nature of primary through μ-poor criterion. The larger array, GRAPES-III (shown in Figure 1), is one of the most dense shower arrays in the world, with detectors arranged in hexagonal configuration with inter-detector separation of only 8 m in an attempt to achieve lower energy threshold ($\sim$ 30 TeV) and good angular resolution at lower primary energies.

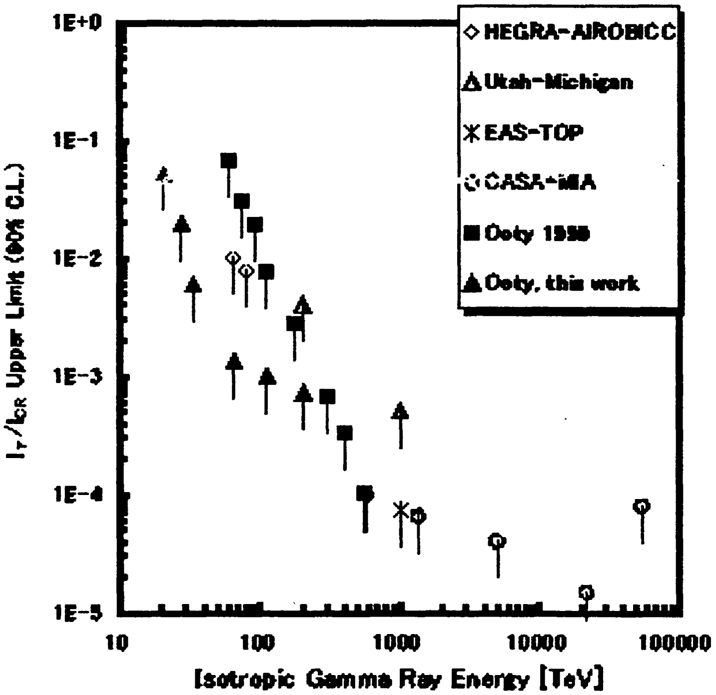

Figure 2. Upper limits on the ratio of the flux of diffuse gamma rays and cosmic ray particles, I_γ / I_{CR}, as a function of γ-ray energy (Hayashi et al 2001).

Most of the shower arrays designed for γ-ray astronomy which became operational in late 1980's and later have incorporated large area muon detectors to enable identification of γ-ray signal through measurement on the muon content of showers. This feature has permitted these experiments to place significant upper limits on the diffuse γ-ray flux which is expected due to interaction (Berezensky et al 1993) of cosmic rays with matter in interstellar space and various radiation fields in intergalactic space. Ong (1998) has summarised the observations from GREX, EAS-TOP, HEGRA, Tibet ASγ and CASA-MIA experiments. The most sensitive upper limit on the ratio of the diffuse γ-ray flux to cosmic ray flux from the galactic plane obtained by the CASA-MIA experiment is 2.2×10^{-5} at energies above 1.8×10^{14} eV. Recently, the GRAPES collaboration (Hayashi et al 2001) has been able to put very stringent limits, shown in Figure 2, on this ratio over a broad energy range, 2×10^{13} eV to 5×10^{14}, exploiting the advantages of the GRAPES-III array, namely, the high altitude (800 g cm^{-2}), high density of shower detectors and very large area and tracking capability of the compact muon detector.

It is relevant to mention here about the striking contrast between the observational reach of γ-ray astronomy at TeV and PeV energies. Due to the expected attenuation of the γ-ray flux through interaction (Gould and Schreder 1966) with radiation fields permeating interstellar and intergalactic space, the reach of observations at PeV is essentially restricted to our own galaxy and relatively nearby space. On the other hand, the TeV flux is not attenuated significantly by the cosmic microwave background radiation thus permitting observation of very distant but very energetic sources such as blazars and other AGN's. However, from the perspective of understanding sources and acceleration of ultra high energy cosmic rays around the *knee*, detailed observations on PeV sources within our own galaxy, even if episodic, is of great importance.

A remarkable development achieved by the new shower arrays mentioned above has been the improvement in the accuracy of measurement of arrival direction of showers. This has been best demonstrated by the observations on the shadow due to the Sun and the Moon by all the new arrays. Very impressive results (Amenomori et al 2000b) have been reported recently from observations with the Tibet ASγ array, which show promise of giving some interesting information on the effects due to geomagnetic field as well as the direction and strength of the Solar magnetic field and their variation with time.

Although μ-poor criterion has been used for γ-ray astronomy at PeV energies, γ-ray initiated showers do have a number of muons (Halzen et al 1997) which may also be used for γ-ray astronomy, particularly at TeV energies. The technique has the natural advantage of having full sensitivity and coverage of a large part of the sky at all times, just like the 'air shower' technique. It is particularly suited for long-term monitoring of 'bursting' sources. In fact, there are several reports (e.g. Thomson et al 1991) of detection of 'episodic' signals in the literature but, unfortunately, these results could not be confirmed by independent observations (e.g. Ahlen et al 1993). However, several of these experiments (Ambrosio et al 1998, Cobb et al 2000) have been able to demonstrate the achievement of good angular resolution and pointing accuracy using this technique. Due to excellent momentum as well as angular resolution, recent observations by the L3+Cosmics collaboration (Timmermans 1999, Le Coultre 2001) using the very large area L3 muon spectrometer are attempting to extend the reach of high energy muons for γ-ray astronomy.

3. Energy Spectrum and Composition at PeV Energies

Ideally, measurement of the flux of each nuclear species as a function of energy over as broad an energy range as possible is required to understand well the physics and astrophysics of the sources of high energy cosmic rays, their acceleration near the sources and their propagation through interstellar and intergalactic space. At lower energies, this has been attempted with detectors flown aboard balloon or satellite-borne platforms. However, practical limitations imposed by the requirement of larger size and weight of detectors with increasing energy and the rapidly decreasing flux have restricted direct observations to energies below $\sim 10^{14}$ eV.

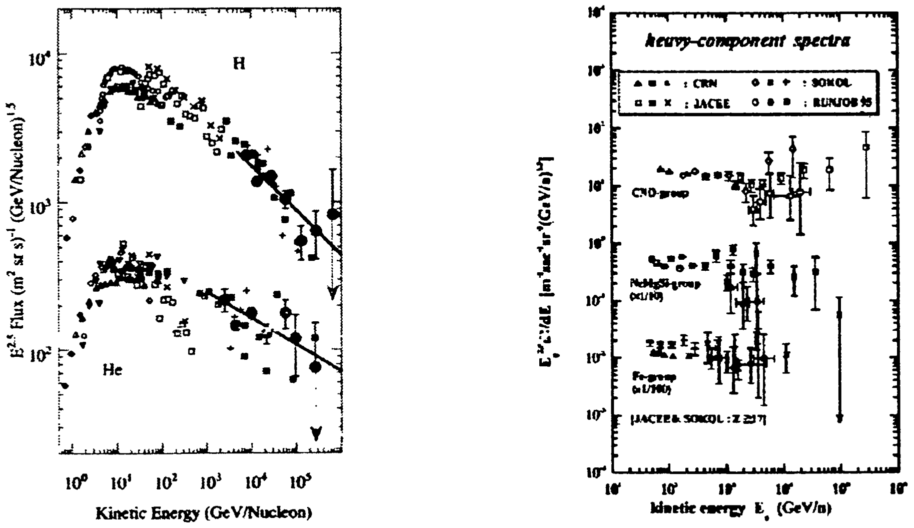

Figure 3. Summary of available measurements on energy spectra for (a) protons and helium nuclei (Asakimori et al 1998) and (b) heavier nuclear groups, CNO, NeMgSi and Fe (Apanasenko et al 1999), made with detectors flown aboard balloon or satellite-borne platforms.

With determined effort and perseverence, the JACEE collaboration (Asakimori et al 1998) has been able to accumulate more than 1400 m^2 hr of exposure for their emulsion chamber system, mostly at altitudes above 5 g cm^{-2}. Figure 3a shows the status of available measurements as summarised by Asakimori et al (1998) for protons and helium nuclei. Note that energy spectra for protons ($E^{-2.80}$) and He nuclei ($E^{-2.68}$) have satisfactory statistics only upto energy $\sim 3 \times 10^{13}$ eV/nucleus. The summary of the available measurements for the three heavier nuclear groups presented (Figure 3b) by the RUNJOB collaboration (Apanasenko et al 1999) shows that data have large statistical errors and large fluctuations beyond energy $\sim 10^{12}$ eV/nucleon. However, spectra for these three nuclear groups seem to be flatter with spectral exponent ~ -2.6 compared to protons and helium nuclei. The statistical precision for most of these measurements is unlikely to improve dramatically over the next few years due to severe experimental difficulties in increasing the exposure factor. Therefore measurements on the energy spectrum and

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composition at energies > 10^{14} eV have to be made indirectly through studies on various components of air showers and correlations between them.

All the five observable components of air showers in the lower atmosphere, namely, electromagnetic, muons, hadrons, Cherenkov photons and nitrogen fluorescence photons, have been used for measurements on the energy spectrum and composition of cosmic ray flux at ultra-high energies (Kampert 2001). Of course, observations on N^2 fluorescence photons have been possible only at energies > 10^{17} eV due to the very feeble signal at lower energies. Various characteristics of the Cherenkov photon component, e.g., the temporal structure and the lateral distribution, and their correlations with the other components, have been extensively studied during the last few years with large arrays (Dickinson et al 1999, Rohring et al 1999, Arqueros et al 2000, Swordy and Kieda 2000, Fowler et al 2001, Shirasaki et al 2001 and others). Most of these observations convert the observable parameters to mean depth of shower maximum (X^{max}) through relations obtained from Monte Carlo simulations. While some of the observations lead to the conclusion that there is practically no change in the composition upto the 'knee' compared to the results obtained from direct observations at lower energies, others suggest a gradual increase in the content of heavier nuclei with increasing energy. Unfortunately, interpretation of observations on the Cherenkov component is very sensitively related to details of analysis procedures and simulations and it is very difficult to estimate the extent of systematic errors in the determination of cosmic ray composition from these observations.

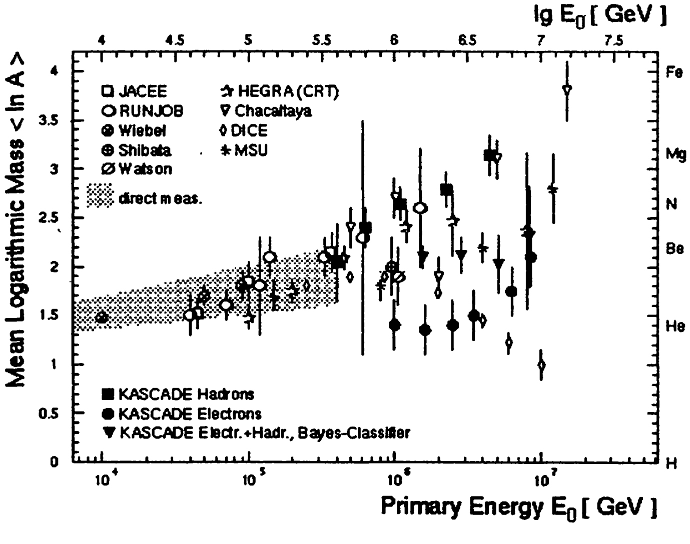

Figure 4. Variation of mean mass of primary cosmic ray flux with primary energy (compilation by Engler et al 1999).

Only a few observations have been made in recent years on the hadron component since early 1980's when the Maryland group (Goodman et al 1979, Freudenreich et al 1990) suggested the gradual enrichment of primary flux with heavier nuclei from studies on the arrival time distribution of hadrons in air showers. Recently, observations with the large calorimeter of the KASKADE experiment have been used to obtain new results (Engler et al 1999) on composition from the high energy hadron component and its correlations with the electromagnetic and muon components. The KASKADE results, summarised in Figure 4 alongwith several other measurements, also suggest the enrichment of primary flux by heavy nuclei with increasing energy above $\sim 3 \times 10^{14}$ eV. Similar conclusions have been drawn by the Tibet ASγ group (Amenomori et al 2000c) and the Mt. Chacaltaya group (Aguirre et al 2000) from studies using emulsion chambers and burst detectors. It may be noted here that the high energy hadron component is very sensitive to details of high energy interactions and due care has to be exercised in the interpretation of observations.

It is now well-known that the muon-component has the highest sensitivity for distinguishing between various primary nuclei, mainly due to two reasons. Firstly, the muon production is enhanced in nuclei-initiated showers due to the fact that secondary particle multiplicity depends only logarithmically on the interaction energy and a shower initiated by a nucleus (total energy E_o, mass number A) is essentially a superposition of A showers, each with energy E_o/A. Further, the decay probability for pions is significantly larger due to their lower energies, on the average, in case of the primary particle being a heavy nucleus. Also, the fact that the electromagnetic component of heavier nuclei-initiated showers reaches its maximum higher in the atmosphere compared to showers initiated by protons or lighter nuclei, makes correlations between the electromagnetic and muon components very sensitive to the nature of primary particles. A large number of observations have been carried out on correlations between these two components since early 1960's to obtain information on composition of primary flux. Unfortunately, most of the early observations were made with small area muon detectors which required averaging over a large number of showers to obtain lateral distributions and muon sizes (N_μ) for various electron size (N_e) groups, losing a lot of sensitivity in the process.

In recent years, several experiments (e.g. BAKSAN, CASA-MIA, EAS-TOP, KASKADE and GRAPES) have used very large area detectors for the muon component, thus improving significantly the quality of measurements on the μ-component. For example, the CASA-MIA experiment (Glasmacher et al 1999) with its very impressive muon detector array of 16 patches, each $\sim 195m^2$ in area, distributed over the area covered by the 1089 electron detector array has made a very detailed analysis and concluded that the average mass increases with energy, becoming heavier above 10^{15} eV.

In contrast to the other experiments, the GRAPES collaboration (Hayashi et al 1999) has installed a single very large area ($560m^2$) tracking muon detector (Figure 1) consisting of 4 alternately crossed-layers of proportional counters which are covered with concrete slabs giving a muon detection energy threshold of 1 GeV. Detailed simulations, using the COSMOS code (Kasahara and Torii 1991, Kasahara 1995) have shown that the muon multiplicity distribution observed with a large area muon detector for showers of a welldefined size group, allows determination of the relative content of lighter and heavier nuclear groups over a limited primary energy range, almost independent of each other.

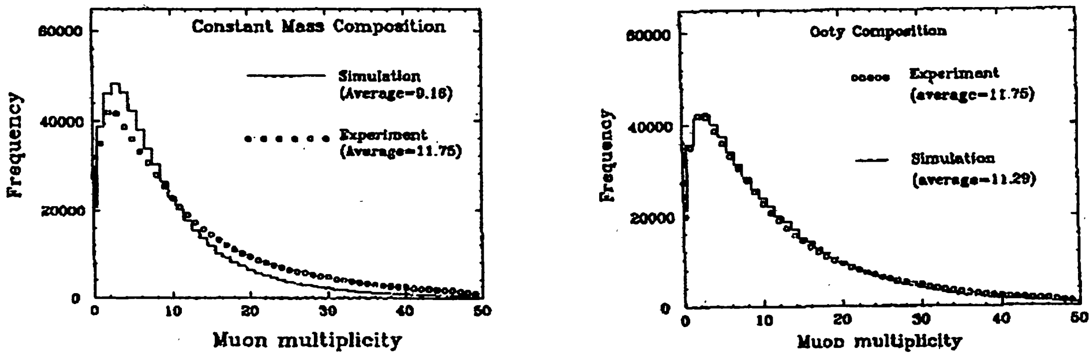

Figure 5. Comparison of the muon multiplicity distribution observed with the GRAPES-II array with expectations from simulations for (a) the constant composition model and (b) the Ooty composition model (Srivatsan 1995).

A simple analysis (Srivatsan 1995) of data obtained with the GRAPES-II array has confirmed these expectations. Though the area of the muon detector in the 100 detector GRAPES-II array is only 200 m^2, it permits quite an accurate determination of the muon multiplicity due to the use of 192 modules of 20 cm deep water Cherenkov detectors, each 1.04 m^2 in area. Using only the shower triggering criterion and the observed shower rate during simulations, the muon multiplicity distribution has shown very good sensitivity to contributions from different nuclear groups in the primary flux. Figure 5a shows a comparison of the observed multiplicity distribution with the expectations based on a 5-component (p, He, N, Si and Fe) model for primary flux. The flux for each component has been normalised to the JACEE flux at 1 TeV/nucleus and a power law spectrum with differential spectral index of -2.7 has been assumed for each species which steepens to -3.0 at a rigidity cut-off value of 2000Z TeV. It may be seen from Figure 5a that fewer showers have been observed with smaller ($n_\mu < 10$) muon multiplicity compared to expectations. On the other hand, the number of observed showers with larger ($n_\mu > 10$) multiplicity are more. This difference is also shown by the observed average number of 11.8 compared to the expected average of 9.2 muons.

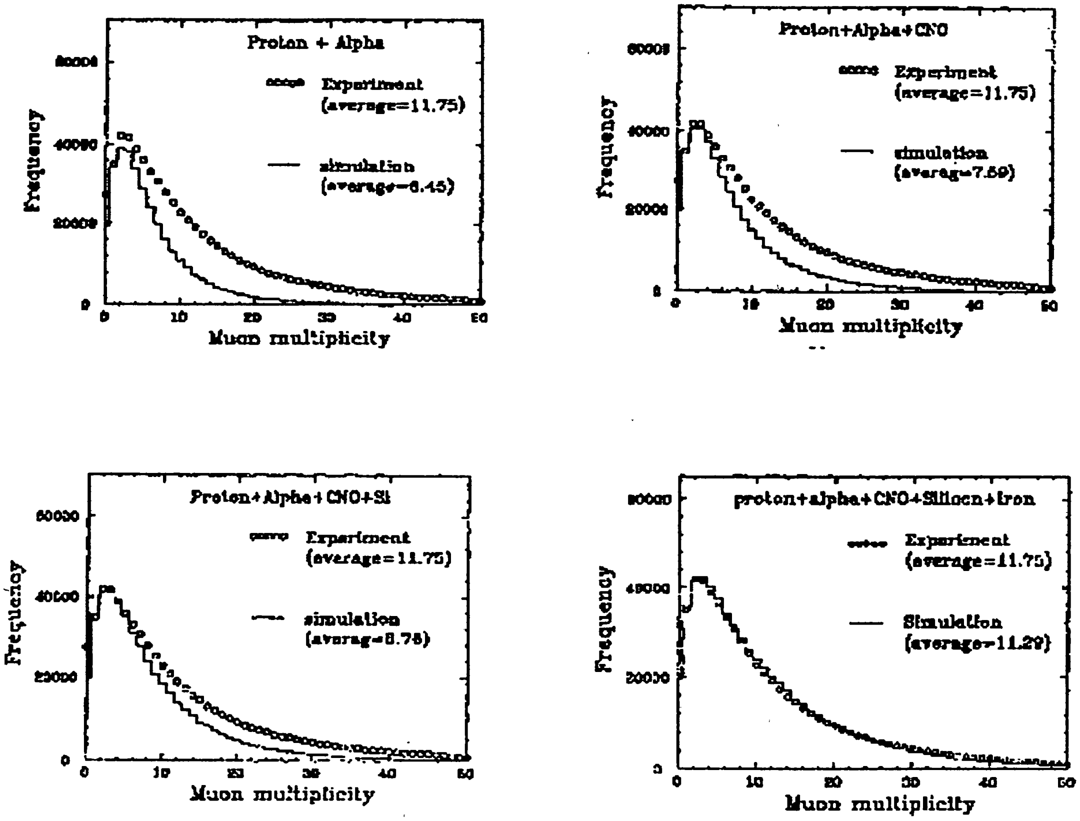

Figure 6. Incremental contributions of various nuclear groups in primary flux to the muon multiplicity distribution obtained from simulations. Points represent experimental data from observations with the GRAPES-II array (Srivatsan 1995).

Simulations using various values of spectral indices for protons and iron nuclei have shown that protons contribute mostly in the $n_\mu \sim 1 - 10$ range in the multiplicity distribution while iron nuclei contribute mostly to the $n_\mu > 10$ region. In fact, it has been possible to obtain a reasonable agreement (figure 5b) between the observed and the expected distributions with a simple rigidity cut-off model, similar to the one proposed by the Maryland group (Freudenreich et al 1990) except for the following difference: the spectral indices for the 5 components were taken to be -2.75, -2.65, -2.65, -2.60 and -2.50 below the rigidity cut-off value of 200Z TeV which increased by 0.5 at energies above the cut-off. The sensitivity of the multiplicity distribution to contributions of different nuclear groups is demonstrated pictorially in Figure 6 by adding a group at a time to the primary flux. Using the spectral values given above, the relative contents of the 5 nuclear groups, p, He, N, Si and Fe, in the primary flux have been computed to be 27%, 23%, 13%, 12% and 25% respectively for the energy interval, 10^{14-15} eV. These values change to 10%, 15%, 15%, 17% and 43% respectively for the higher energy decade, 10^{15-16} eV. Therefore the mean value of '**ln A**' changes from 3.01 in the lower energy decade to 3.45 in the higher energy decade. In other words, the proportion of the heavier nuclear groups

(Si+Fe) in the primary flux increases from 37% to 60% over this energy range. More detailed analysis of data from both the GRAPES-II and GRAPES-III experiments is in progress to obtain the variation of composition in finer energy intervals over the broad energy range, $3 \times 10^{13} - 3 \times 10^{16}$ eV.

Attempts have also been made to study the composition of primary cosmic ray flux from multiplicity distribution for very high energy muons observed with detectors located deep underground, e.g., MACRO (Ambrosio et al 1997), Soudan 2 (Kasahara et al 1997) and KGF (Adarkar et al 1998). Unfortunately, these impressive and high resolution detectors designed and constructed for searches for proton decays, magnetic monopoles and other exotic physics, did not have any information on showers accompanying the observed muons. Therefore interpretation of observed muon multiplicity distributions suffers from too few constraints on possible range of models of primary energy spectra for various nuclear groups.

The L3+Cosmics experiment (Le Coultre 2001), which finished data taking in November 2000, holds the promise of providing completely new information on the high energy muon component in air showers. The large area precision muon spectrometer of the L3 experiment at LEP (CERN) has been used by the L3+C group to measure the momentum spectrum and multiplicity distribution for high energy (30-1500 GeV/c) muons in showers observed with an extensive air shower array on surface. Results on composition of primary flux over the energy range $\sim 10^{14} - 3 \times 10^{15}$ eV from the L3+C experiment would be eagerly awaited by the cosmic ray community.

4. Summary

The observation of an almost continuous energy spectrum for the cosmic ray flux over more than 10 decades of energy with the exception of the two features, the *'knee'* and the *'ankle'*, poses an exciting challenge for understanding the sources of cosmic ray particles and their acceleration and propagation in space. A review of the results of searches for discrete sources of cosmic gamma rays at PeV energies leads to the conclusion that ultra-high energy sources are mostly episodic in nature. It is therefore felt that potential sources like X-ray binaries should continue to be monitored with sensitive shower arrays around the world. The other sources of information on the nature of cosmic ray accelerators are the energy spectra for various nuclei present in the primary flux. In recent years, several large arrays have been operated around the world for measurements on energy spectrum and composition in different energy regions. Combined with excellent results reported in recent years from CASA-MIA (including DICE and BLANCA), EAS-TOP, HEGRA, BAKSAN and other experiments, the ongoing observations with Tibet ASγ, SPASE-VULCAN, KASKADE, L3+Cosmics, MILAGRO, GRAPES and other experiments hold the promise to lead to a better understanding of the energy spectrum and composition at energies $\sim 10^{14-16}$ eV. It is hoped that new theoretical developments incorporating the new results from observations would then contribute towards significant advancement in our understanding of the ultra high energy cosmic accelerators.

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