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COSMIC γ-RAYS AND COSMIC NUCLEI ABOVE 1 TeV

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ABSTRACT

This paper is based on a rapporteur talk given at the 19th International Cosmic Ray Conference in August 1985. In it the most exciting and controversial aspects of work on cosmic γ-rays and cosmic nuclei above 1 TeV are described and evaluated. The prospect that γ-ray astronomy above 1 TeV will give new insights into high energy cosmic ray origin within our galaxy is particularly bright.

1. *Introduction*. The search for the origin of cosmic rays has been a long and conspicuously unsuccessful one. At high energies ($> 10^{14}$ eV) it had been anticipated that careful study of the small anisotropies which are present, allied with a sound knowledge of the mass composition and energy spectrum, would yield indirect information about the sources. At the very highest energies ($> 10^{19}$ eV), where the Larmor radii of protons in galactic magnetic fields exceed 3 kpc, strong directional anisotropies had been expected if the sources of these multi-joule particles were galactic, while a sharp cut-off in the spectrum above about 4×10^{19} eV has been predicted if the sources were at cosmological distances. Of the three measureable parameters, spectrum, anisotropy and mass composition, only the first can even now be said to be well-known (although the question of the Greisen-Zatsepin cut-off remains under debate) and our understanding of the data available on arrival directions continues to be hampered by very limited knowledge about the primary mass composition.

At the Bangalore conference it was recognized that perhaps a fourth channel of information about cosmic ray origin was opening to us. At that meeting evidence of γ-ray emission at ∿1 TeV from several sources, including the Crab pulsar and Cygnus X-3, was reported. In addition the possibility that point sources of γ-rays up to 10^{16} eV might exist had been signalled through the claim by the Kiel group (Samorski and Stamm 1983a) of emission from Cygnus X-3 of 10^{15} eV γ-rays modulated with the 4.8^h orbital period of the binary X-ray source. The significance of this latter result, confirmed by Lloyd-Evans et al (1983) by the time of the Bangalore meeting, is that it seems impossible to explain the γ-rays as arising from other than π^0-decay. Thus for the first time a source of cosmic ray nuclei may have been identified. Not surprisingly this meeting has seen the fruits of the burgeoning interest in γ-rays above 1 TeV while work on cosmic ray nuclei has continued with all its former vigour. I have thus had to be very selective in choosing the topics discussed below but they are, I believe, the most stimulating and controversial culled from a particularly vigorous area of the cosmic ray field.

2. Gamma-ray emission above 1 TeV. The idea that there should be detectable sources of γ-ray emission above 1 TeV is an old one. At the Moscow conference Cocconi (1959) proposed that particle arrays of adequate angular resolution should be built at high altitude, with the aim of searching for point sources of γ-rays. In particular he estimated that a

flux of $\sim 10^{-7}$ photons $cm^{-2}\ s^{-1}$ above 1 TeV was expected from the Crab Nebula. To workers at that time the idea seemed beyond the limits of technical feasibility, but it prompted Chudakov and Zatšepin in the Soviet Union to develop searchlight mirror/photomultiplier combinations to search for cosmic ray point sources using the atmospheric Cerenkov light produced by γ-ray initiated air showers. This technique had been pioneered in Britain by Galbraith and Jelley (1953) for the study of more energetic cosmic rays. These searches were not immediately rewarded but in 1972 Stepanyan and colleagues at the Crimean Astrophysical Observatory (CAO), using the Cerenkov method, reported the detection of Cygnus X-3 in a flaring state following the 1972 radio outburst and, on many subsequent occasions, with the 4.8^h modulation of intensity known since the 1968 Uhuru observations at X-ray energies. At this conference γ-ray emission from many objects has been claimed and I have space to review details about only a few of them; results on others will merely be stated.

2.1. Cygnus X-3. By far the most attention has been given to observations of Cygnus X-3 - partly because it is a strong source and visible from the Northern hemisphere - but also because details of its binary nature are reasonably well understood. Above 500 GeV measurements have been reported by 14 independent groups and in addition it has received much theoretical attention. It is believed to be the site of nucleonic acceleration (up to 10^{17} eV/nucleon) and possibly the major cosmic ray source active in our galaxy at the present time. Furthermore, in one of the most exciting announcements made at a cosmic ray conference for many years, the Durham group reported evidence of a pulsar within the source of period 12.5908 ± 0.0003 ms (Chadwick et al, submitted to Nature, July 1985).

Cygnus X-3 has been extensively studied at X-ray energies since its discovery by the Uhuru satellite in 1968. The X-ray emission is modulated in an approximately sinusoidal manner with a period close to 4.8 hours. This period is believed to be associated with the co-rotation of a neutron star and a star of several solar masses. The peak of X-ray emission occurs at a phase $\phi \simeq 0.65$ with respect to the time of X-ray minimum ($\phi = 0$) at which the X-ray intensity is $\sim 40\%$ that at maximum. A detailed analysis of the X-ray behaviour, as deduced from EXOSAT observations, has been given by Willingale et al (1985) and the long term behaviour, as observed by the Vela 5B satellite, has been reported by Priedhorsky and Terrell (1986).

Observations above 500 GeV are made using the air-Cerenkov technique (500 GeV - 30 TeV) and with conventional air-shower arrays (30 TeV - 10 PeV; 1 PeV $\equiv 10^{15}$ eV). Typical light curves over the 4.8^h period are shown in Figure 1 for some of the experiments described at this meeting. The light curves show much sharper peaks than the near-sinusoidal emission pattern seen at X-ray energies. In all the data there are peaks close to $\phi \simeq 0.65$, the peak of the X-ray emission. The results at 3×10^{13} eV from the group at the Whipple Observatory, Mt. Hopkins, are of particular interest as they were taken with ultra violet filters during a period close to full moon. The technique has yet to be calibrated so that the energy estimate is only approximate but if it can be further developed it will provide a very useful overlap with the EAS method which comes in at a similar energy. All these data have been

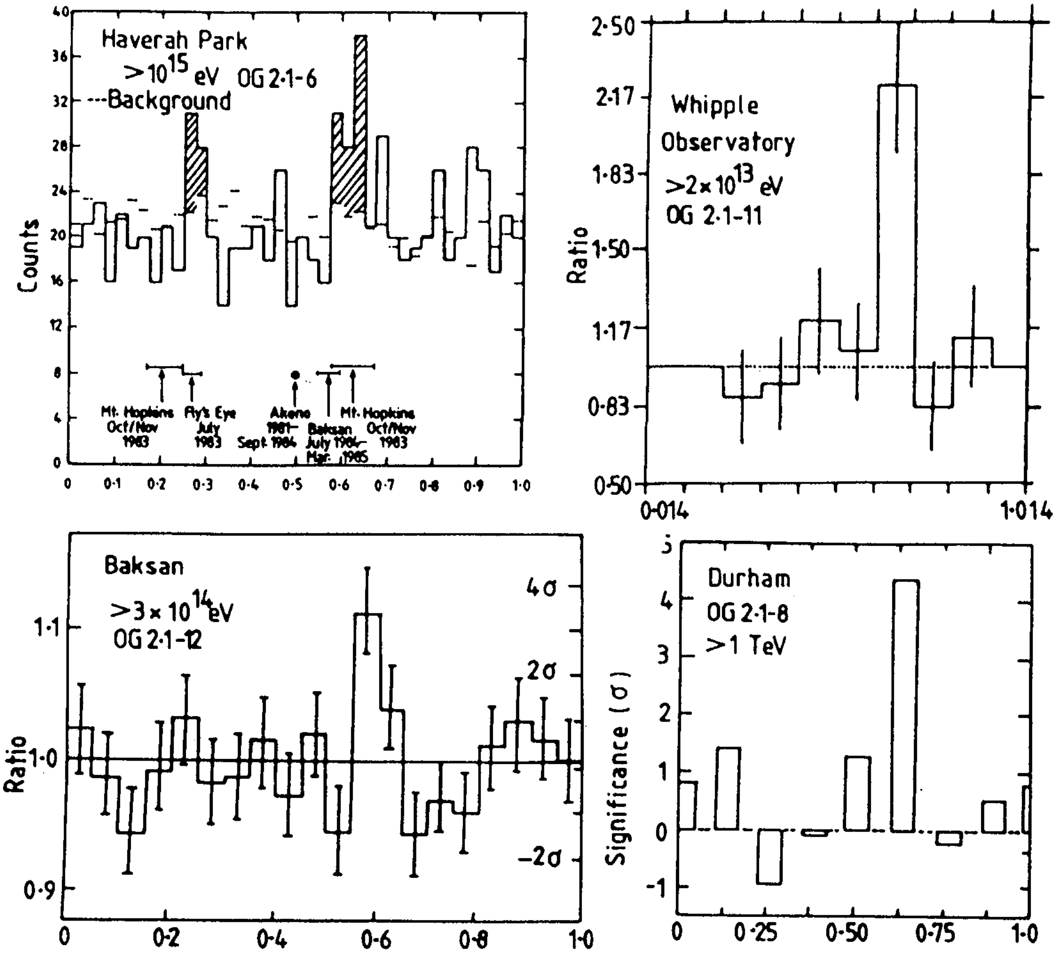


Figure 1: Cygnus X-3 light curves as determined from recent observations at different energies.

analysed using an ephemeris derived by van der Klis and Bonnet-Bidaud (1981) from a number of satellite observations and it is recommended that this ephemeris (or revised versions of it) be used in all data reduction on this source to restrict confusion when comparing results from different experiments.

The integral spectrum of Cygnus X-3 above hard X-ray energies (> 20 keV) to beyond 10 PeV is shown in Figure 2. The X-ray data (Reppin et al 1979, Meegan et al 1979) from balloon flights in October 1977 are represented by integral spectra derived from the published differential spectra. The measurements of Reppin et al are time-averaged over the phase interval 0.18 to 0.60 observed during one 2 hour period of the balloon flight while measurements of Meegan et al, covering the interval 0.45 to 0.91, have been averaged over the 4.8^h cycle to conform with the practice above 500 GeV. The difference in slope and intensity between the two hard X-ray

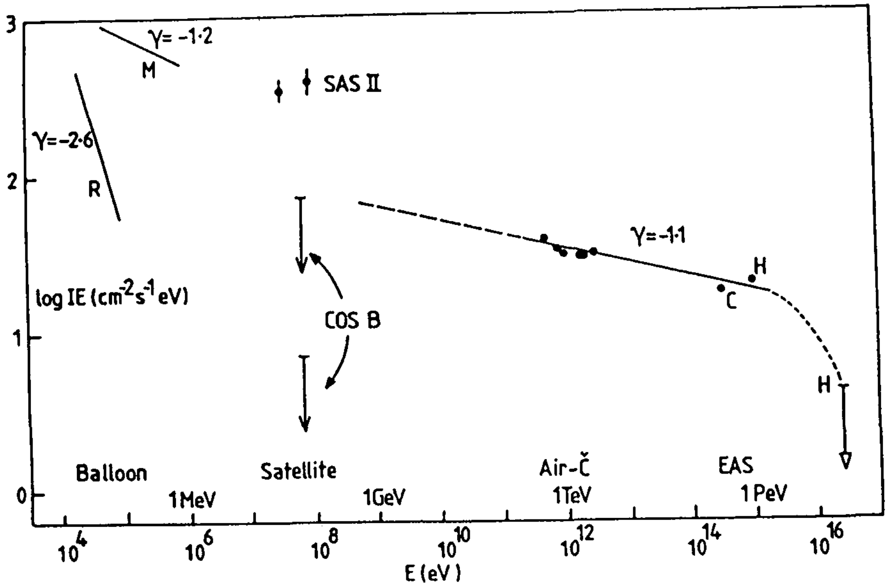


Figure 2: The integral spectrum of Cygnus X-3 above hard X-ray energies. R (Reppin et al 1979); M (Meegan et al (1979); SAS II (Lamb et al 1977), COS B (OG 2.2-2); points near 10^{12} eV (see caption of Figure 5); C: Baksan (OG 2.1-12); H: Haverah Park (OG 2.1-6).

measurements made at different phases in the orbital period is regarded as real (Meegan et al 1979) and, coupled with the known flux variability at lower X-ray energies, complicates the question of what should be the extrapolated flux in the region of the COS B and SAS II experiments. The possibility that the SAS II observations are genuine and conform to a high γ-ray state for Cygnus X-3 during 1973 (R.C. Lamb, private communication) is not excluded from examination of these data although a contrary view has been stressed forcefully by the COS B collaboration (OG 2.2-2) at this conference. All measurements shown above 500 GeV were made post-1979; the 6 points at around 1 TeV are from independent observations (see caption of Figure 5 for details). Above 10^{14} eV the measurements shown are from the Baksan (C) (OG 2.1-12) and Haverah Park (H) (OG 2.1-6) experiments which were nearly contemporaneous (C: July '84 to Feb '85; H: 1984) and for which the energy calibration is reasonably firm. Above 500 GeV the source spectrum is likely to be quite different from the spectrum at the top of the atmosphere as there is the complication of γ-ray absorption ($\gamma + \gamma \rightarrow e^{+} + e^{-}$). At TeV energies optical photons close to the source may suppress the signal (Apparao 1984) while near 10^{15} eV the mean free path for absorption by the 2.7K background ($\lambda \sim 7$ kpc) is less than the lower limit of 11 kpc set to the source distance (Dickey 1984). At intermediate energies we may have to worry about the presence of a significant flux of far-infrared photons in the waveband not explored by the IRAS survey. The energy output of the source is difficult to assess in view of these uncertainties. However, the slope of the spectra is very flat above 1 TeV and the flux above 1 PeV is $\simeq 10^{37}$ erg s^{-1}.

It is difficult to summarise all of the data above 500 GeV succinctly as one possibility which has emerged at this meeting is that Cygnus X-3 may be time-variable both in the nature of its light curve and its amplitude. It is, of course, disappointing (and powerful material for the sceptics) to discover that this remarkable object is time-variable but I believe this to be an experimental fact (and one which sets severe demands on the type of experiment which we should be thinking of doing in the future).

Before addressing the time-variability evidence I will attempt to summarise data on the light curve in broad terms. Near 1 TeV recent measurements (post-1980) have tended to show a strong, relatively broad, peak ($\Delta\phi \gtrsim 0.1$) near $\phi \simeq 0.6$ although there have been reports of significant effects at $\phi \simeq 0.2$, particularly in the pre-1980 data of Stepanyan's group. There is some evidence that when a signal is seen near $\phi \simeq 0.2$ the initiating γ-rays are of higher energy than those seen at $\phi \simeq 0.6$. Above 10^{15} eV emission has been seen near both $\phi \simeq 0.2$ (1976 - 1983) and at $\phi \simeq 0.6$ (1984) and the peak of emission appears to be narrower ($\Delta\phi < 0.1$ and sometimes ~ 0.03) than at lower energies. The phase information is likely to be of major importance in modelling of the source and the available data are summarised in Figure 3. The evidence for emission near $\phi \simeq 0.25$ and $\phi \simeq 0.65$ is compelling. The significance of each signal (in sigma) has been taken directly, or estimated, from the published light curves. In the case of the Kiel experiment (K) (Samorski and Stamm (1983a)) account has been taken of their 4.4σ detection of the source before phase analysis. All data have been analysed using the van der Klis/Bonnet-Bidaud ephemeris except for the Akeno (A) and Kashmiri data (B) for which the probable phase adjustments are indicated by arrows.

I have also marked on the diagram the phase band in which the Soudan group (Marshak et al 1985) and the NUSEX group (Battisoni et al OG2.1-3) have reported a peak in a time-modulated signal seen in their underground muon detectors. Clearly whatever is the cause of this signal it cannot be some anomaly in γ-nucleon cross-sections or there would be phase coincidence. However if the mechanism suggested by Stecker et al (1985) works, and the signal is enhanced beyond straightforward expectation, it might be worth looking for the neutrino events expected at large zenith angles in the underground data in narrow phase windows centred on the γ-ray phases.

The most exciting result reported during the sessions on Cygnus X-3 was that of the Durham group (Chadwick et al 1985) who claim to have detected within the TeV emission the long-sought pulsar in the Cygnus X-3 system. Figure 4 is from their discovery preprint and shows the probability of agreement with a uniform distribution as a function of period for a 7 minute stretch of data near $\phi = 0.65$ taken on 12 Sept 1983. The evidence for a pulsar of period 12.5908 ms looks strong and is supported by similar data taken on 2 October 1983. Both observations were made close to the time of maximum of the 18.7 day period claimed

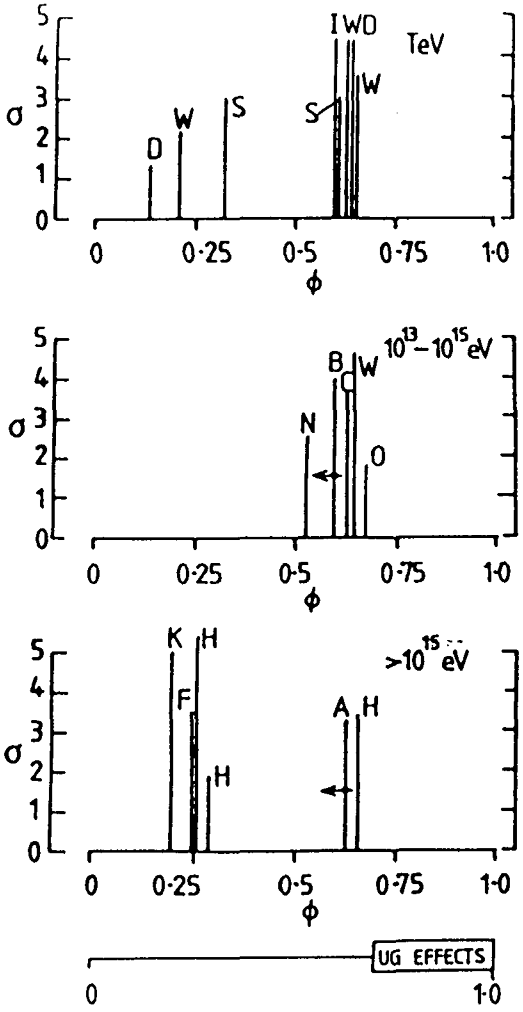


Figure 3: Summary of phase of maximum γ-ray emission from Cygnus X-3. D (Durham), W (Whipple Observatory), S (Stepanyan), I (Riverside/ JPL/Iowa State), N (Plateau Rosa), B (Khasmir), C (Baksan), O (Ooty), K (Kiel), F (Fly's Eye), A (Akeno) and H (Haverah Park). The phase of the underground muon signal claimed by Soudan and NUSEX is shown by 'UG effects'.

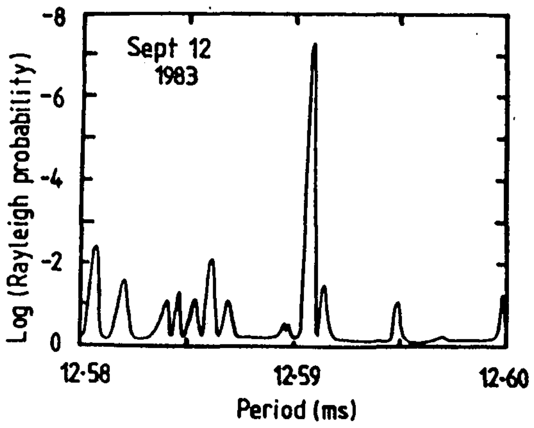


Figure 4: The chance probability for periodicity in 450 events containing the count rate excess from Cygnus X-3 as a function of trial period (from Chadwick et al 1985).

for the source (Bonnet-Bidaud and van der Klis 1981). This result, stated to have a probability of $< 3.10^{-7}$ of arising by chance, obviously supplies a major constraint to models of particle acceleration within the source.

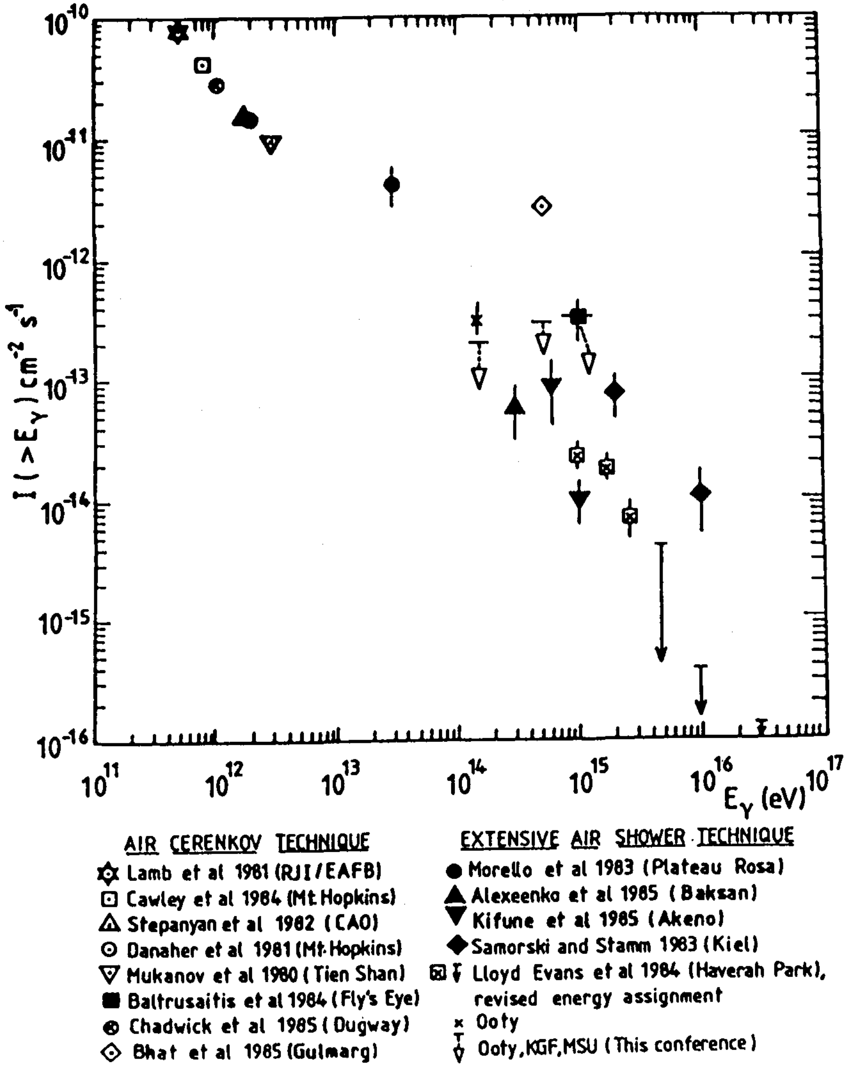
The phase picture (Figure 3) is reasonably tidy but the same cannot be said of the situation with regard to flux. The experiments used for Figure 3 have all (with the exception of the Whipple Observatory result at 3×10^{13} eV) provided intensity estimates (so far only in integral form because of the limited statistics) and these are shown in Figure 5. Clearly there is considerable scatter between the results reported by different groups at a particular energy. Two major reasons for the scatter are poor statistics and uncertain energy calibration; these difficulties will surely disappear in time.

An extreme explanation for the scatter in Figure 5 has been advanced by Bhat et al (OG 2.10-10) who suggest - largely on the basis of their own measurements with an uncollimated light collection system - that the flux above 10^{13} eV is decaying exponentially with a time constant of 1.7 ± 4 years. Most models of Cygnus X-3 couple the presence of TeV γ-rays to the production of 10^{15} eV γ-rays, through what Hillas (1984) has described as an extensive stellar shower, and it is hard to reconcile the decay proposed by Bhat et al with the relative constancy of the TeV signal between 1972 and 1985. Factors of 2 or 3 variations have been seen but a change of the magnitude proposed (> 450) over this period is not credible. Furthermore above 10^{15} eV the Haverah Park group (OG 2.1-6) have observed essentially the same flux between 1979 and 1982 as in 1984 (but at a different phase).

There is, however, convincing evidence of a less dramatic nature for amplitude and phase variations on a time-scale of months. The Mt. Hopkins group observed a 4.4σ effect at $\phi \simeq 0.6$ in the Oct/Nov 1983 dark period but no signal was detectable with identical equipment and similar observing conditions during the Nov/Dec 1983 dark period (Cawley et al 1985). This group reported a similar effect in 1981 (Weekes et al 1981). The Fly's Eye group, working at 10^{15} eV, found a 3.5σ effect during 9-13 July 1983 at $\phi \simeq 0.25$ but observing nothing during the dark periods of August and September 1984. The Haverah Park group observed a change of the preferred phase of emission between 1979-1982 ($\phi \simeq 0.25$) and 1984 ($\phi \simeq 0.66$, with weak emission at $\phi \simeq 0.29$). It is interesting to note that the Mt. Hopkins result was obtained just after the 1983 Sept/Oct radio flare and that similar enhancements of TeV emission have been reported previously after other flares (Vladimirsky et al 1973 (following the famous 1972 flare) and Fomin et al 1981 (after the 1980 flare)).

Preliminary analysis of an observation of a flare from Cyg X-3 in which a flux level of 6×10^{-11} cm^{-2} s^{-1} was measured above 3×10^{13} eV was reported at this meeting by the Fly's Eye group. This event was seen on 16 June 1985 during one of 13 nights of observation. Even at this level of intensity existing air shower arrays would have great difficulty in detecting such a signal: an array of 30 m radius and angular resolution 10^{-2} sr, sensitive above 300 TeV would expect to record only about 3 Cygnus events above a general cosmic ray background of about 1 event! The Fly's Eye event did not show pulsed emission and may be of the genre of the shorter flare transients observed by Nesphor et al (1979), Weekes (1982) and the Durham group (Gibson et al 1982).

Figure 5: Time averaged integral γ ray spectrum above 5×10^{11}eV from Cygnus X-3.



I know of no group who have observed Cygnus X-3 and reported a null result at an intensity level which contradicts those shown in Figure 2 and conclude that this source is indeed a γ-ray emitter above 500 GeV and probably up to 10 PeV. There remain, however, some questions to be answered about data from the PeV region before the matter can be regarded as being finally settled; these are:-

(a) Muon content of γ-ray showers:- The Kiel group (Samorski and Stamm 1983b) reported that their Cygnus X-3 events had a muon content ∿ 80% that of 'normal' showers, a result which was in sharp contradiction with theoretical expectation and is now questioned further by data from the Akeno group (OG 2.1-5) who were able to detect Cygnus X-3 only after selection of events having a muon/electron ratio less than 1/30 of that found in the bulk of showers. The Nottingham group (OG 2.1-4), hampered by poor statistics, a poor signal/noise ratio, and the small area ($10\,m^2$) of muon detector presently available at Haverah Park, have been unable to make a statement about the muon-content in the small number of Haverah Park events for which there is coincident data. It is not clear how to resolve this question but the possibility that some of the signal seen in the Kiel detector (which is not a tracking detector) may be due to 'punch-through' of very low energy photons ($\gtrsim 10\,keV$) does not yet seem to have been eliminated. Some relevant experimental data have been discussed (HE 4.5-1) by the Nottingham group but more are needed.

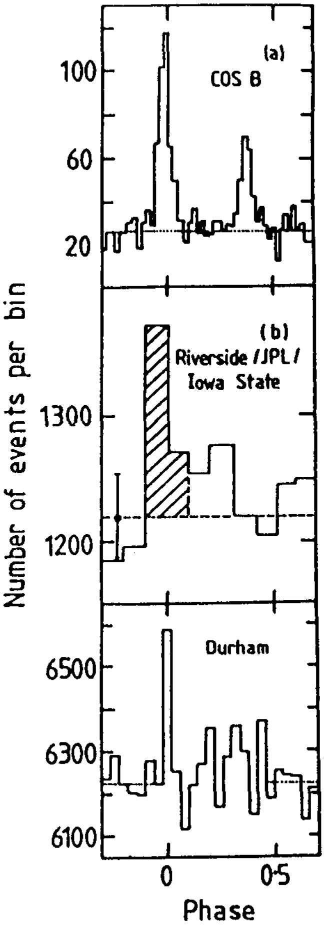
(b) Age selection of γ-ray showers:- The Kiel group adopted the selection requirement that the shower age, s, should be greater than 1.1 in the expectation of enhancing the γ-ray content of their sample. A similar cut was used by the Adelaide group in their detection of Vela X-1 (Protheroe et al 1984). The justification for this approach is not clear and indeed the Ooty group (OG 2.6-8) find their most significant signal ($\sim 1.5\sigma$ at $\phi = 0.675$) when showers of all ages are used. However the Ooty array is at a depth of $800\,g\,cm^{-2}$ and it may be that the age restriction is effective for data taken at sea-level. Further theoretical study of this problem would be helpful.

(c) The source ephemeris:- For their discovery paper the Kiel group used the ephemeris of Parsignault et al (1976) and had not corrected their data to the heliocentre. Subsequent reanalysis after heliocentric correction and with the van der Klis/Bonnet-Bidaud ephemeris broadens the peak in phase and shifts it to the interval 0.1 to 0.3. However, the 4.4σ detection before phase analysis is unaffected and overall the Kiel result remains significant.

An overview of the Cygnus X-3 situation,with particular emphasis on what can be inferred about the production of γ-rays within the source,is available in the written version of the 'Highlight Talk' of A.M. Hillas elsewhere in this volume. Theoretical studies of the object are reviewed by V.S. Ptuskin in his rapporteur paper.

2.2. The Crab Nebula and Pulsar (PSR 0523+21). As usual in γ-ray astronomy the Crab Nebula and pulsar have attracted considerable attention. Prior to this conference the Durham group (Dowthwaite et al 1984a) had reported strong evidence of a pulsar signal from the Crab above 1 TeV with a light curve which peaked in coincidence with the main pulse of the radio emission. In a further report (OG 2.3-9) they lay particular stress on the extreme narrowness (< 0.4 ms) of the emission peak. This result is shown in Figure 6 together with the light curve at 100 MeV from COS B (Wills et al 1982) and the new result from the Riverside/JPL/Iowa State group (OG 2.3-3) at 200 GeV. The latter light curve also exhibits a single peak although a broader one than found by the Durham group. The fluxes reported by both groups (RJI (> 200 GeV) = $(2.5 \pm 0.8) \times 10^{-11}$ $cm^{-2}s^{-1}$ and Durham (> 1 TeV) = $(7.9 \pm 1.8) \times 10^{-11}$ $cm^{-2}s^{-1}$) are compatible.

Figure 6: The light curve of PSR 0523+21 as measured at 100 MeV (COS B), 200 GeV (Riverside/JPL/Iowa State) and 1 TeV (Durham). For references, see text.



The Crab pulsar has also been studied by the Tata group (OG 2.3-4) at ∿1 TeV. Results were reported orally. During an extended series of observations in 1984-85 they were able to detect no pulsed signal within the sum of their data. However between 1711 and 1726 UT on 23 Jan 1985 they detected pulsed emission at the level of 5.1σ with the emission peak coincident with the radio peak. This group have also reported (OG 2.3-4/5) the continued detection of 'microbursts' from the Crab first discussed at the Bangalore conference. A microburst is defined to be the occurrence of 4 consecutive events with less than 1.5 ms between successive events. Over 100 such microbursts have been detected in 57 hours at a rate more than twice the background rate. These detections have not been replicated at Mt. Hopkins. The Tata group are continuing observations with two similar detector systems separated by 11 km.

Above 400 GeV the Mt. Hopkins group (OG 2.3-1), using a new algorithm to reject non γ-ray events, have reported a convincing (5.6σ) DC signal at a flux level of 6×10^{-11} $cm^{-2}s^{-1}$. Above 3×10^{13} eV Morello et al (OG 2.2-12), using conventional air shower techniques, have obtained a DC upper limit of 10^{-11} $cm^{-2}s^{-1}$. At higher energies the Tien Shan group (OG 2.3-2) have used the muon-poor technique to optimise a γ-ray signal from the Crab direction ($\alpha, \delta \pm 7.5^{\circ}$) above 3.5×10^{14} eV and 5.5×10^{14} eV. These results, based on 12 events, are plotted in Figure 7 together with the flux reported above 10^{16} eV by the Lodz group (Dzikowski et al 1981) and upper limits obtained in other experiments. Also included is a typical pair of data from the earlier Fly's Eye experiment (Boone et al 1984) in which emission was observed (3.1σ) on 9 December 1980 but not during February 1981. Even the very hard ($\gamma \simeq 0.8$) spectrum inferred from the Tien Shan/Mt. Hopkins result cannot be reconciled with the Lodz claim which is also strongly contradicted (factor of 200) by Haverah Park work (OG 2.6-9). Future studies with the improved Haverah Park γ-ray array (OG 9.4-7) in which a pulsed detection will be sought may clarify this situation before the next conference. Note, that the angular resolution in the Tien Shan, Lodz and Fly's Eye experiments are much poorer than that at the Mt. Hopkins so that there is no convincing evidence that the signals claimed by these groups are associated with the nebula.

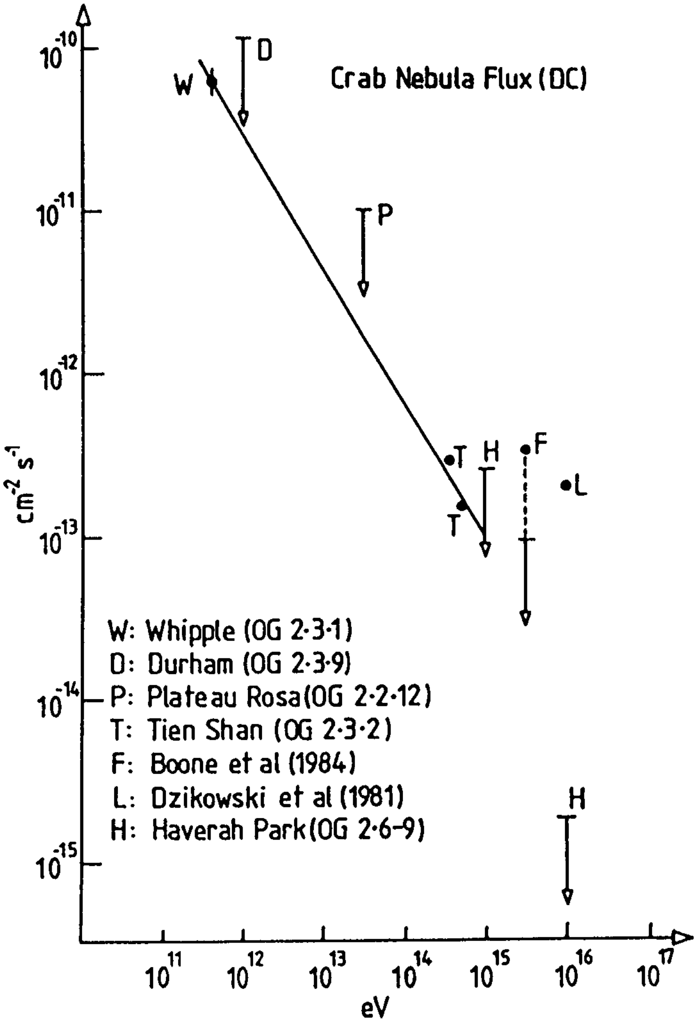


Figure 7: The integral energy spectrum of γ-rays from the Crab nebula. The solid line is an eyeball fit to W and T and has $\gamma \simeq -0.8$.

2.3. Observations on other sources.

Many other sources have been observed using the techniques of very high energy ($\sim$1TeV) and ultra high energy γ-ray astronomy. A number of upper limits have been set (for example the Durham group (OG 2.3-9) have reported upper limits at about 2×10^{-11} $cm^{-2}\,s^{-1}$ on 7 radio pulsars) but there are 8 objects (in addition to Cygnus X-3 and the Crab) from which positive effects have been claimed; two of these (both in the Southern hemisphere) have been examined only above 1 PeV. Details of the observations are given in Table 1.

Lamb and Weekes (1985) have suggested that 4U0115+63 (a transient X-ray source) is to be identified with Cas γ-1, a TeV source reported previously by the CAO group (Stepanyan et al 1972). This proposal further emphasises Stepanyan's role in founding very high energy γ-ray astronomy. The Vela pulsar (PSR 0833-45) appears to be variable at TeV energies but its detection is probably secure. Of the sources in this list which have been detected above 1 PeV there is need for confirmations in all cases. Her X-1 was not observed by the Durham group in an observing period contemporaneous with the Fly's Eye detection. There is some evidence in the Chacaltaya data (OG 5.3-2) to support the Vela X-1 detection by the Adelaide group; 11 events are seen in a box ($\Delta\alpha = 30^{o}$, $\Delta\delta = 20^{o}$) centred on the source when 5.2 are expected. A phase analysis is not supportive but the ephemeris cannot be extrapolated to 1967 (the time of the Chacaltaya observations) with confidence. LMC X-4 is reported above 10^{16} eV; the significance is claimed at 1% and the source would be 20 times as powerful as Cygnus X-3.

Table 1

Summary of detections of sources other than Cyg X-3 and Crab Nebula

Object	Reference	Significance/chance probability at ∿TeV	at ∿PeV	Comments and Periodicity
4U0115+63	Durham (OG 2.6-11)	2.5×10^{-6}	-	Pulsar: 3.6 s
	CAO (Stepanyan et al (1972))	3.9σ on Cas γ-1	-	DC Cas γ-1 ≡ 4U0115+63 (Lamb & Weekes 1985)
PSR 1953	Durham (OG 2.6-11)	5.4σ	-	Pulsar: 6.1 ms Binary: 117.3 days
PSR 0833-45	SAO/Sydney (Grindlay et al 1975a)	Variable	-	Pulsar: 89 ms
	Tata group (OG 2.3-10)	99.3% CL		
M31	Durham (Dowthwaite et al 1984b)	1% $2.2 \pm 0.7 \times 10^{-10} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ at 1 TeV	-	DC not confirmed by Mt. Hopkins
	Mt. Hopkins (OG 2.7-3)	$< 1.6 \times 10^{-10} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ at 400 GeV		
Her X-1	Durham (OG 2.6-11) (Dowthwaite et al 1984c)	7×10^{-5} (17 April 1983)		Short bursts at pulsar period: 1.24 s
	Mt. Hopkins (OG 2.2-9)	2×10^{-4} (4 April, 5 May 1984)		
	Fly's Eye (OG 2.2-7) (Baltrusaitis et al 1985)	-	2.10^{-4} (11 July 1983)	Durham observation contemporaneous with Fly's Eye saw *no* signal
Vela X-1	Adelaide (Protheroe et al 1984)	-	10^{-4}	Binary: 8.96 d
LMC X-4	Adelaide (OG 2.6-10) (Protheroe & Clay 1985)	-	1%	Binary: 1.4 d
Cen A	SAO Sydney (Grindlay et al 1975b)	4.5σ ($> 10^{11}$ eV)		DC
	Adelaide (Clay et al 1984)	-	2.7σ (10^{16} eV)	DC, *but* ultra high luminosity unless IG magnetic field is low ($<< 10^{-7}$ G)

I have not listed Geminga (2CG195+4), the brightest unidentified source in the COS B catalogue, in Table 1. The detections reported near 1 TeV (OG 2.4-2, OG 2.4-5) are inconsistent and unconvincing and no DC or pulsed signal has been detected by the Mt. Hopkins group at 400 GeV (OG 2.4-4). Recently Buccheri et al (1985) have pointed out some of the statistical pitfalls that await the unwary who study this source and at the moment there appears to be no firm evidence at low energy of periodicity near 59.5 sec with which to support the statistically weak TeV claims.

2.4. Summary of sources above 1 TeV. There are at least 6 sources (Cyg

X-3, Crab nebula and pulsar, Her X-1, 4U0115+63, PSR 1953 and the Vela pulsar) for which the claimed detections near 1 TeV can be said to be quite firm. At ∿1 PeV and above confirmatory detections have been made only for Cyg X-3 (and there remain some unanswered questions, see section 2.1). Of the 6 strongest candidates two are pulsars and four are X-ray binaries. In the case of the X-ray binaries the similarity of their light curves (Figure 8) has led to the suggestion that all such objects are TeV γ-ray emitters (see, for example, A.M. Hillas, Highlight Talk). The light curve observed at higher energy by the Fly's Eye group is quite different with a peak at $\phi = 0.75$ in the 1.24 s period.

Models of proton 'beam dumps' in precessing accretion disks are being developed by many authors to explain the complex features of these sources (Brecher and Chanmugan, OG 2.2-5; Eichler and Vestrand, OG 2.2-8).

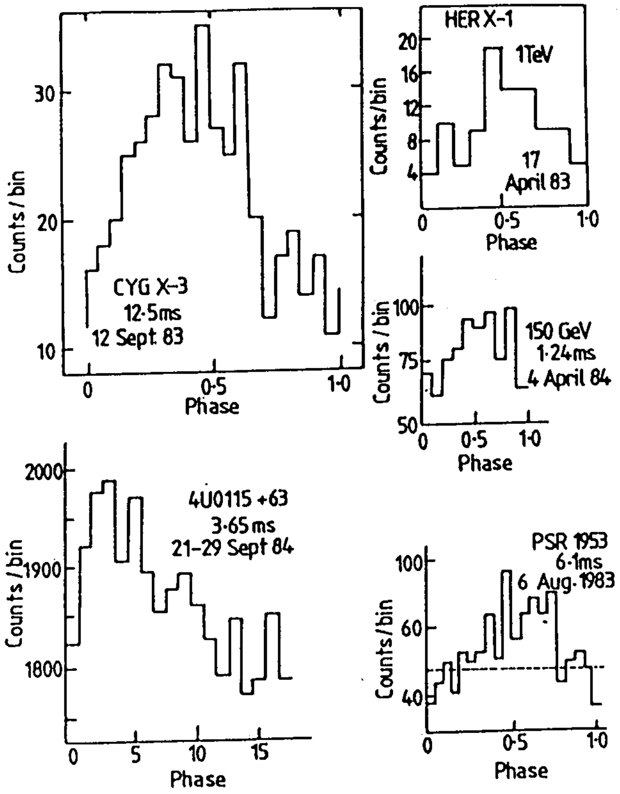


Figure 8: The light curves of TeV γ-rays from 4 binary X-ray pulsars. The period of each pulsar and the date of each observation is shown in the diagram. All observations (except Her X-1 on 4 April 1984) are by the Durham group. See Table 1 for references.

2.5. The future of γ-ray astronomy above 1 TeV. The future success of γ-ray astronomy at ∿1 TeV seems assured. New experiments are funded for the Durham group (in Australia) and the Potchefstroom group (South Africa) to survey the Southern Hemisphere sources and there are many plans to extend existing facilities and build new ones in the Northern Hemisphere.

While TeV astronomy is a healthy youngster, by contrast PeV astronomy is only in its infant stages. Above 100 TeV a few air shower arrays, having angular resolution approaching 1° and of area $> 10^{4}\ \mathrm{m}^{2}$, are operating, or soon will be, but it is important to recognize that $10^{4}\ \mathrm{m}^{2}$ is only about the area monitored by existing TeV telescopes where the flux is at least 100 times higher. Thus, with the exception of the Fly's Eye instrument, these arrays are too small for serious study of short time-scale phenomena which have proved such a rich field of work in astrophysics since the discovery of pulsars in 1968. By 1987 (the Moscow Conference) I predict that Cygnus X-3 will be clearly established as a PeV source but the rest of the sky will be strewn with doubtful '3 sigma' detections where confirmation has been difficult to get because of the limited sky region ($\pm 40^{\circ}$ in declination) available to any detector, poor statistics, and time variability. Lest such a situation continue (and the whole subject became faintly disreputable) there should be a concerted effort, probably requiring international collaboration, to build a number of large γ-ray facilities at different latitudes. By large I mean about $1\ \mathrm{km}^{2}$ (with $> 10^{3}$ detectors); such an array would detect about 10 γ-rays above 3×10^{14} eV from Cygnus X-3 per 4.8 hour cycle. (The present world total of γ-rays above this energy is probably less than 200.) Hillas pointed out to me (and I know others have realized it too) that the South Pole is an ideal place for seeing X-ray binaries: there are plenty to see, they are 'up' all day and the altitude (~ 2500 m) is about right! With such areas we may even anticipate detecting sources which have not been seen at other wavelengths (as did COS B).

Why is PeV γ-ray astronomy of more importance to cosmic ray physics than TeV astronomy? The answer is simple. I suspect that many clever theorists can explain TeV emission through electron synchrotron or curvature radiation but none (yet) has suggested that PeV γ-rays can arise from other than π^{0}-decay. We thus have the prospect of taking a major step in solving the cosmic ray origin problem while at the same time linking our subject very securely to the mainstream of astrophysics: I hope this is a chance we will not miss.

3. Can γ-rays explain cosmic ray anisotropy? Soon after the early reports of ultra high energy γ-ray emission from Cygnus X-3 and other objects Wdowczyk and Wolfendale (1983) pointed out that as the γ-ray spectra from various sources appeared to be flatter than the cosmic nuclei spectra then the γ/p ratio would increase with energy so that much of the anisotropy, hitherto attributed to the nucleonic component, might be due to γ-rays. At this meeting (OG 5.4-11) they have extended and quantified their discussion. Below $\sim 10^{13}$ eV it seems probable that the observed anisotropy ($\sim 0.1\%$) is due to the nucleonic component because the majority of measurements have been made using underground detector systems. Between 10^{13} and 10^{15} eV observations have usually been made at mountain altitude so that the nature of the primaries causing the observed anisotropy is open and γ-rays might contribute. Alexeenko and Navarra (1985) have obtained a remarkably good fit to the anisotropy observed between 10^{13} and 10^{14} eV by extrapolating the diffuse γ-ray flux measured by the COS B satellite. The best experimental data in this energy range are those from the Baksan experiment (Alexeenko et al 1984) from which the following 1st and 2nd harmonics in right

ascension have been reported:-

$$\begin{array}{lcll} a_1 = (5.8 \pm 0.3) \times 10^{-4} & & \theta_1 = 1.2 \pm 0.2\,\mathrm{h} & \\ & \text{with maxima at} & & \text{in sidereal} \\ a_2 = (1.6 \pm 0.3) \times 10^{-4} & & \theta_2 = 6.1 \pm 0.5\,\mathrm{h} & \text{time.} \end{array}$$

The fit achieved is shown in Figure 9; there is no normalisation so that the agreement between prediction and observation is particularly striking. However, until more is known about the spectrum of the ultra high energy γ-ray sources, this interpretation of the observed anisotropy can only be considered as tentative.

Indeed it is not entirely clear what the characteristics of a γ-ray anisotropy above 10^{13} eV should be. Very recently Bhat, Kifune and Wolfendale (1985) have suggested that the latitude dependence may be a complex function of γ-ray energy. For example at 7×10^{15} eV severe synchrotron losses suffered by electrons in the magnetic field of the galactic disk lead to the prediction that the γ-ray flux at $b = 0^{\circ}$ will be nearly an order of magnitude lower than at $b = 30^{\circ}$; these statements apply to longitudes near 0°. Better data are needed to test these predictions.

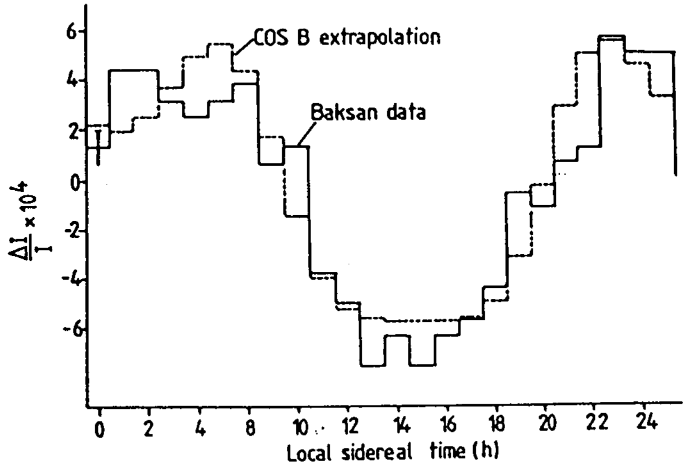


Figure 9: (after Alexeenko and Navarra 1985)
The cosmic ray sidereal daily variation, shown as departures from the mean, is compared with the extrapolated COS B measurement of the diffuse flux from the galactic plane.

To determine γ-ray anisotropies with certainty requires experiments which are sufficiently sensitive to isolate those 10^{-3} or so of events which are γ-ray initiated from the general cosmic ray background. The approach which has usually been adopted - but about which there must now be some doubt in view of the μ-poor/Soudan-effect controversy with regard to Cygnus X-3 - makes use of the expectation that γ-ray initiated showers are deficient in muons by comparison with those initiated by nuclei. Some success with this technique has been achieved in the case of Cygnus X-3 by the Akeno group (OG 2.1-5) as mentioned above. At this meeting the Lodz group (OG 2.6-7) (using $14\,\mathrm{m}^2$ of muon detector with a 0.5 GeV threshold and $40\,\mathrm{m}^2$ with 5 GeV threshold) have claimed an excess of events above expectation in the latitude range $|b < 17.5^{\circ}|$ when showers are selected with 0-3 muons. The effect is an excess of 234 events over about 2300 expected in this latitude strip. Formally this is a 5σ signal but the latitude strip was not picked 'a priori' and appears to have been chosen to maximise the effect. Also it is not clear that normalisation of the experimental histograms, made in the latitude interval 17.5 - 77.5°, is justified. These data are shown in Figure 10; the effect is confined to showers with electron number $> 10^6$ ($E \gtrsim 5.10^{15}$ eV).

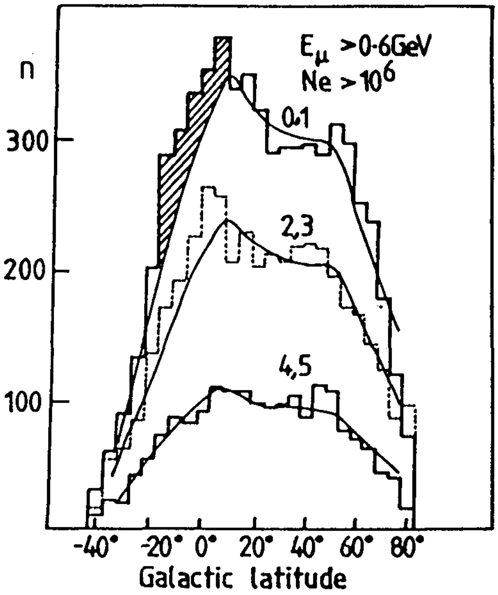


Figure 10: (from OG 2.6-7) Galactic latitude distribution of showers with $N_e > 10^6$ and various numbers of muons > 0.6 GeV. The excess claimed as due to γ-rays is shaded on the 0, 1 muon histogram.

A similar 'μ-poor' approach was developed many years ago at Chacaltaya using the 60 m² muon detector located there. Updated results have been reported here (OG 5.3-2) for $E \sim 10^{15}$ eV. A peak, based on 269 low-mu showers, is noted at RA = 210° when data are summed over the 70 degrees of declination scanned in the experiment. It is not totally compelling (confidence level = 91%) in the absence of any 'a priori' expectation that it should be seen in that direction. The authors note that the preferred direction is close to the direction of the maximum of the 1st harmonic for all showers recorded with $3 \times 10^{16} < E < 10^{18}$ eV. The Yakutsk group (OG 5.1-14) using 108 m² of muon detector (threshold 1 GeV) have begun a study of the muon content of showers produced by primaries $> 10^{17}$ eV. So far from 10^3 events they have identified one in which the muon content is 12 times less than normal. The galactic co-ordinates of the primary are (153°, -8°) and, if really a γ-ray, the intensity is about 3×10^{-14} m^{-2} s^{-1} sr^{-1}.

An alternative explanation to the γ-ray proposal for explaining anisotropies close to the 'knee' in the energy spectrum has been forwarded by Clay (OG 5.4-10). He shows that for data near 10^{15} eV the peaks in the distribution lie close to the 'spiral-in' direction on the galactic plane while the two measurements in the Southern Hemisphere exhibit troughs in the 'spiral-out' direction. He interprets this observation as implying that cosmic ray flow at these energies is diffusive with its source in the inward spiral arm direction.

4. Primary mass composition > 1 TeV. Below about 100 TeV/nucleus the primary mass composition can be measured rather directly using balloon or satellite exposures. At higher energies inferences about the

composition have to be drawn from the properties of air showers observed at ground level or from muons observed underground. The information from direct measurements is summarised in Table 2 where a measure of the mean mass, $< \ln A >$, which is appropriate for discussions of shower data about 100 TeV (Linsley 1983; Linsley and Fichtel OG 5.4-4), has been adopted.

Table 2

Mass composition above 1 TeV from direct measurement

Energy (TeV)	$< \ln A >$
1	1.50
10	1.68
100	1.57 ± 0.3

The first two data are from the summary of Juliusson (1975); the 100 TeV estimate is from the direct but limited statistics exposures of the JACEE project (Burnett et al 1982). There is no evidence for any enrichment of the primaries by heavy nuclei between 10 and 100 TeV and the enrichment between 1 TeV and > 10 TeV can be understood either in terms of a diminished path length at higher energies, resulting in reduced fragmentation of the heavier nuclei, or in terms of a change in the source spectrum. The experimental situation between 1 and 100 TeV has changed little since the last conference.

As a basis for discussion of the mass composition above 100 TeV I have reproduced in Figure 11 part of a figure from OG 5.4-4 (Linsley and Fichtel). Here $< \ln A >$ is shown as decreasing above 2×10^6 GeV, where the value is about 1.7, to a value near 0 (pure protons) above 10^7 GeV. Although the bulk of the data come from an interpretation of one experiment (Acharya et al 1983 and OG 5.2-10) the conclusion is supported by reviews of the variation of depth of shower maximum (X_m) with energy (e.g. Kvashnin et al 1983) made before this meeting which showed that the elongation rate, the rate of increase of X_m with energy, changed from about 120 $\mathrm{g\,cm^{-2}}$/decade below 10^{17} eV to about 60 $\mathrm{g\,cm^{-2}}$/decade above 10^{17} eV. Such a change requires a decrease in $< \ln A >$ of about 1.5 between 10^{15} and 10^{17} eV.

Further support for a mass composition lighter above 10^{15} eV than below comes from an analysis made by Hillas (1984a) of the integral spectrum of shower size (N) observed at different atmospheric depths. He has shown that an explanation of the absolute rates and the shape of the shower size spectrum can be given in terms of a bimodal mass model in which the Fe-spectrum steepens from $\gamma = 2.7$ to 3.3 at 1.8×10^{15} eV/nucleus and the proton spectrum steepens from 2.7 to 3.1 at 5×10^{15} eV. Above 10^{15} eV these spectra, with 40% protons, fit the data on size spectra from depths in the range 540 - 1030 $\mathrm{g\,cm^{-2}}$. Note that the Fe-spectrum steepens before the proton spectrum on this model, counter to the frequently discussed rigidity model in which the Fe and proton spectra steepen at the same rigidity. On the Hillas model the knee at 5×10^{15} eV reflects a feature of the proton spectrum, <u>not</u> the Fe-spectrum. If the proton knee is due to rigidity dependent-galactic leakage then the break in the Fe-spectrum must be explained some other

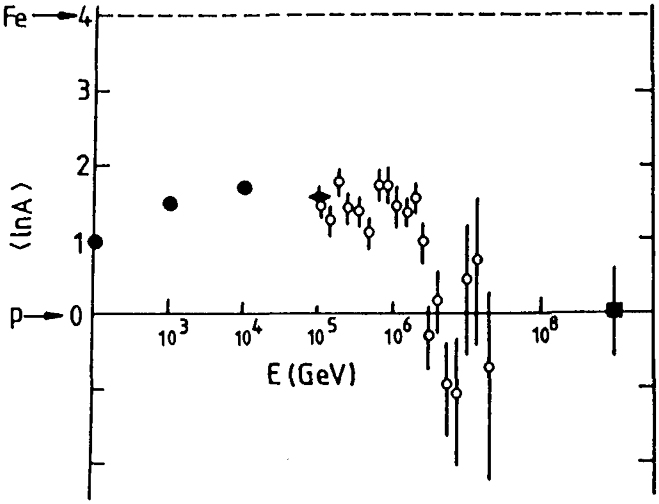


Figure 11: (from OG 5.4-4) The energy dependence of $< \ln A >$ closed circles, balloon experiments; diamond, JACEE; open circles, Acharya et al (1983); square, Linsley and Watson (1981).

way. Hillas proposes that the Fe-knee may be intrinsic to the source. One possibility which has been explored in OG 5.2-10 is that the break in the iron-spectrum (and in the spectra of nuclei down to He) arises from photo-disintegration. In this paper Acharya et al confirm Hillas's analysis of the number spectra data and supplement their interpretation with their measurements of the number of 220 GeV muons in showers of size $10^4 < N < 10^7$. The variation of N_μ (> 220 GeV) with N is believed to be nearly twice as sensitive to changes in mass composition as the variation of N_μ (< 10 GeV) with N, which is more often measured (Grieder 1983). Acharya et al find a discontinuity in their N_μ-N plot which is explicable in terms of a break in the Fe-spectrum at about 3×10^{15} eV. Other support for a lighter composition above 10^{16} eV come from work at Yakutsk: Dyakonov et al (OG 5.1-13) claim >85% protons above 10^{18} eV while Glushkov et al (OG 5.1-14) have evidence for >40% protons beyond 10^{17} eV. Similarly from an analysis of N_μ-N data Muraki (OG 5.1-12) has concluded that Fe does not dominate between 2.10^{16} and 2.10^{17} eV.

The discussion of the last two paragraphs might be taken to imply that there is a consensus that the mass composition is lighter above 10^{15} eV than below it. While that is my own view I must point out that there are several papers in these proceedings which argue the counter view, namely that Fe-nuclei begin to dominate beyond 10^{15} eV, i.e. it is an iron-knee rather than a proton-knee. For example the Adelaide group (OG 5.2-11) have measured the lateral distribution of Cerenkov light produced by showers in the energy range 10^{15} to 5×10^{16} eV and derived the distribution of X_m. They have explored the triggering biases of their experiment using Monte Carlo calculations and claim, assuming a bimodal composition, that a mixture of 95% Fe and 5% protons produces a distribution consistent with the data. The Maryland group have been arguing for some years that Fe-nuclei become more dominant above the knee in the energy spectrum. In the latest discussion of their experiment on delayed hadrons in showers (OG 5.2-2) the Maryland group use Monte Carlo calculations to predict the shower rate and the 'delayed event' rate. Very satisfactory agreement is found with an input composition in which there are rigidity spectral breaks for all components (p, α, CNO, Si, Fe) at 200 TeV. The proton spectrum is steeper than the Fe-spectrum both before and beyond the break (γ(p): -2.75 to -3.33; γ(Fe): -2.55 to -3.1). Additionally they claim that such input spectra propagate to produce number spectra in agreement with mountain altitude and sea-level measurements. This latter result is in direct contradiction to that of Hillas (1984a) just discussed. The Mt. Fuji group, from an analysis of γ-ray families having $10^2 < \Sigma E_\gamma < 5 \times 10^3$ TeV, argue that the proton spectra must steepen at around 10^{14} eV. There is also controversy over the experimental data on N_μ (> 200 GeV) vs N. While the Tata group (OG 5.2-10) find a flattening of the N_μ vs N plot near $N = 3 \times 10^5$ no such feature is evident in magnetic spectrograph data reported by the Moscow group (OG 5.2-10).

It should be clear from the above discussion that the answer to the mass composition question above 10^{15} eV is still uncertain. Not all of the experimental data can be correct and there must be large systematic effects in several experiments. There is no agreement about a common shower model to use when analysing data and it is certainly naive to assume that a bimodal composition is the appropriate model to explore above 10^{15} eV. However it is perhaps worth emphasising that no-one is advocating the view that above 10^{18} eV the primaries are all iron. The Fly's Eye group (OG 5.1-2) ($\sim$ 40% protons) and the Yakutsk group (OG 5.1-13) ($\sim$ 85% protons) support earlier claims by the Haverah Park group (Walker and Watson 1983) for at least 40% protons at 10^{19} eV. Above 10^{14} eV progress could perhaps best be made by a long exposure (LDEF?) of a JACEE module.

Further discussions of mass composition above 10^{14} eV are contained in the rapporteur papers of R.W. Clay and T. Stanev in these proceedings. Work relevant to the problem is to be found in the OG and HE volumes.

4. Can anisotropy measurements tell us anything about mass composition?

It has been recognized since the early sixties that studies of muon-poor and muon-rich showers might reveal anisotropies associated with γ-rays and heavy nuclei (A > 12) respectively. The latter measurements make use of the galactic magnetic field as a sort of magnetic spectrometer.[†] One of the design aims of the Akeno array (Kamata 1977) was to exploit this possibility through the construction of $9 \times 25\ \mathrm{m}^2$ muon detectors with threshold energy 1 GeV. The success of this enterprise in the context of γ-ray astronomy has already been referred to and at this meeting new results on the anisotropy of μ-rich showers have been reported (OG 5.3-3). These extend, and partially confirm, results on this topic reported at the Bangalore conference (Hara et al 1983a) and recently submitted for publication (Kifune et al 1985a). The work is continuing and an interpretation of the data so far presented (Kifune et al 1985b and orally at this conference) can doubtless be further refined but I

[†] *The possibility of using the solar magnetic field in this context has been examined quantitatively at this meeting independently by Lloyd-Evans (OG 5.1-9) and by Linsley (OG 9.5-7).*

wish to discuss it in some detail as it appears to offer a different approach to the study of mass composition which may eventually relieve the somewhat pessimistic picture of this subject just painted.

In the first of two experiments the Akeno group (1981 - 82) used an electron trigger sensitive to showers with $N > 3 \times 10^5$. For 2.4×10^5 events having $3 \times 10^5 < N < 6.8 \times 10^6$ they found the mean N_μ/N_e to be 0.03. Of these 2.2×10^4 having $N_\mu/N_e > 0.06$ were defined to be μ-rich and assumed to have been initiated by primaries enriched in heavy nuclei. These events (9.1% of the total) exhibit a large and very significant anisotropy in right ascension: $a_1 = 4.0 \pm 1.0\%$, $\theta_1 = 226 \pm 14^\circ$ RA with chance probability of 2×10^{-4}. This amplitude is for showers of median energy $\simeq 5.5 \times 10^{15}$ eV and is larger by a factor of about 10 than that for all showers of this energy (see Watson 1984 for a summary). Furthermore, as Kifune et al (1985b) have emphasised, the phase is quite different from the best estimate of the phase at an energy E/Z lower in energy. Taking Z = 10 the phase at 5.5×10^{14} eV of about $300 \pm 20^\circ$ (Linsley and Watson 1977) is to be compared with $226 \pm 14^\circ$ found in the Akeno experiment. Anisotropies measured at 5.5×10^{14} eV probably refer to the proton component so that Kifune et al suggest that the phase difference indicates a different origin for the two components.

Kifune et al go on to estimate the fraction of heavy nuclei (A > 12) in the primary beam. The fraction of heavies (F_H) is related to the fraction of μ-rich showers selected (η), the relative proton and heavy nucleus shower sizes at fixed energy (ε) and the efficiency of selection of heavy primaries (g) through the equation $F_H = \eta \varepsilon g$. Adopting values appropriate to the range of experimental data available from Akeno, Tokyo and Haverah Park, estimates of the fraction of heavies as a function of energy have been derived as shown in Figure 12. A lower limit to the heavy fraction comes from the assumption that the heavy nuclei have the maximum possible (point-source) anisotropy.

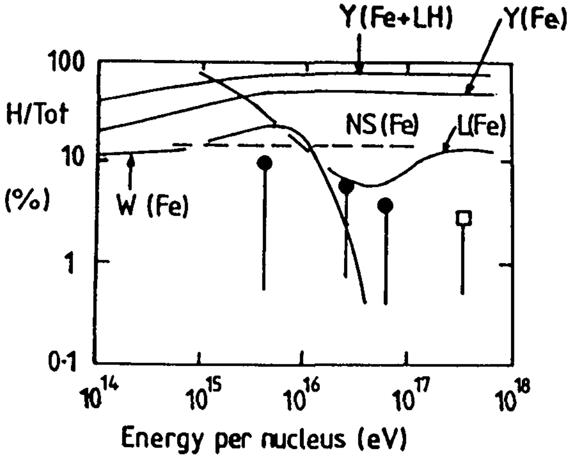


Figure 12: (from Kifune, Wdowczyk and Wolfendale 1985) Y: Yodh et al (1984) NS: Nikolskii and Stanev (1983) L: Linsley (1981) W: Wdowczyk (1985). Data points are derived as outlined in the text; the last two use measurements by Hasegawa et al (1961) and Blake et al (1975).

In a second experiment (1983-84) described in OG 5.3-3 the Akeno group used a trigger in which 4 muons were required in each of $4 \times 9\,m^2$ detectors. This selection was chosen to determine the primary energy more exactly and to reduce the effects of shower development fluctuations. A μ-rich sample, of similar median energy, was again defined by requiring $N_\mu/N_e > 2 < N_\mu/N_e >$: for this trigger 33% of the initial 6×10^4 events were thus selected. Although the phase of the sample was similar ($216 \pm 34^\circ$ RA) the amplitude was smaller and less significant ($1.7 \pm 1.0\%$, $p \simeq 0.25$). Because of the effects of shower fluctuations in the first experiment it is not clear that a cut which retains 33% of the events was appropriate and perhaps a deeper cut (< 10%) should have been used. The result of the second experiment does not weaken the major conclusion of the first experiment which is that muon-rich events produced by primaries of $E \sim 5 \times 10^{15}$ eV have a stronger anisotropy than the bulk of cosmic rays of this energy and also have a different phase from protons of similar rigidity. Although the composition estimates of Figure 12 may require revision, the technique offers real hope that anisotropy measurements can yield valuable information on mass composition.

5. The primary energy spectrum. Measurements of the primary spectrum continue to attract attention. The main points of interest are its detailed shape near the 'knee' and above 10^{19} eV.

5.1. The spectrum from $10^{14} - 10^{18}$ eV. The Adelaide (OG 5.1-6) and Samarkand (HE 4.4-14) groups have carried out measurements near the knee in the spectrum at about 5×10^{15} eV. Both of these determinations are based on the Cerenkov light technique and although dependent on assumptions about mass composition and particle physics they are in reasonable accord with previous work. The Samarkand measurement ($\gamma = -2.6$) supports the view that the spectrum before the knee is somewhat flatter than the spectrum at energies less than 10^{14}eV. The differential spectrum, from $10^{14} - 10^{20}$ eV, is shown in Figure 13. The absolute intensity of the all-particle spectrum is probably known to within 20% in the region of the knee. Also shown are 6 points derived by Linsley (OG 5.1-4) from a calorimetric analysis. These data are in excellent agreement with previous estimates of intensities between 5.10^{15} and 10^{18} eV. The Akeno result (Nagano et al 1985) lies about 10% below these estimates; this must be regarded as excellent agreement considering the difficulties of these measurements. Overall a reasonable description of the spectrum from 10^{16} eV (beyond the knee) to about 10^{19} eV is given by

$$J = 2.1 \times 10^7\, E^{-3.08}\, m^{-2} s^{-1} sr^{-1} GeV^{-1}, \text{ where E is measured in GeV.}$$

5.2. The energy spectrum above 10^{18} eV. At this meeting four groups have reported spectra which contain relatively large amounts of data beyond 10^{19} eV. These results are relevant to the shape of the spectra and in particular to the question of the Greisen/Zatsepin cut-off. The exposures achieved at the various arrays are given in Table 3.

A particular feature of this conference has been the wide range of results reported by the Fly's Eye group. They are to be congratulated on bringing into successful operation a unique instrument which images

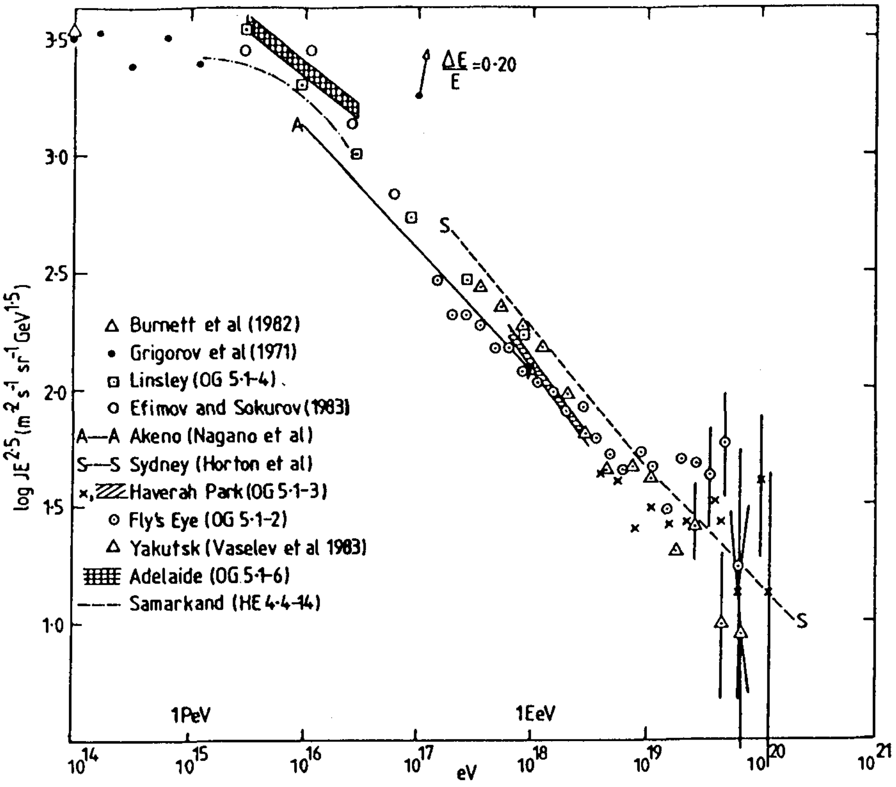


Figure 13: The differential energy spectrum from $10^{14} - 10^{20}$ eV. No attempt has been made to normalise data from different experiments. A systematic change in the energy assignment of 20% would shift each point as shown by the arrow; such a systematic effect could well be present in any data set and probably accounts for much of the scatter.

Table 3

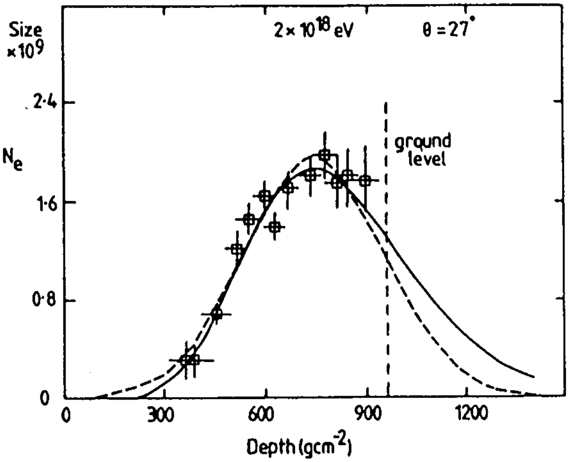
Array	Exposure (km^2 y sr)	Events $>10^{20}$ eV
Volcano Ranch	∿100	1
Haverah Park (OG 5.1-3)	320 ($\theta < 45°$)	4
	660 (used for anisotropy)	8
Yakutsk (OG 5.1-17)	200	0
Sydney (Horton et al 1985a)	1000	8
Fly's Eye (Baltrusaitis et al 1985a)	145	0
	Total	17

the development of air-showers in the atmosphere through the fluorescence light which they produce. For the first time individual cascade curves of reasonable precision are available. A typical cascade curve (HE 4.4-1), reconstructed with data from two 'Eyes' separated by 3.3 km, is shown in Figure 14. This curve is for a 2×10^{18} eV primary at 27°; the depth of maximum is estimated to be (740 ± 40) g cm^{-2}.

Figure 14:

(from HE 4.4-1)

A cascade curve produced by a 2.10^{18} eV primary as observed by Fly's Eye I and II. The depth of maximum is estimated as (740 ± 40) g cm^{-2}.



The effective aperture of the Fly's Eye device varies with energy and must be evaluated by detailed Monte Carlo calculations. The spectrum reported just prior to the meeting (Baltrusaitis et al 1985a) and in OG 5.1-2 is reproduced in Figure 15 except that the error bars, which corresponded to ± $\sqrt{n}$ (n = event number) in these papers, have been replaced by lines which indicate 68% confidence bands, following the recommendation of Regener (1951). The 95% and 84% upper limits have also been added for the differential bin above that which contains a single event. In my view there is insufficient evidence to justify a claim for observation of a 'cut-off' or bump in the spectrum (Baltrusaitis et al 1985) and in his highlight talk Cassiday described a slightly revised version of the Fly's Eye spectrum in terms of a power law between $10^{17} < E < 5 \times 10^{19}$ eV with slope = -3.02 ± 0.02, the error estimate being statistical only. This spectral slope is somewhat flatter than that found by the Sydney group (Winn, Highlight Talk and Horton et al 1985a). A comparison of the two measurements is made in Figure 16; for this figure (unlike Figure 13) the Sydney energies have been re-estimated using Yakutsk data (Diminstein et al 1983) on N_μ vs E (Linsley 1983).

In Figure 17 the Fly's Eye spectrum is compared with that from Haverah Park (OG 5.1-3) and in Figure 18 the Haverah Park and Yakutsk spectra are shown. The Yakutsk spectrum is taken from Vaselev et al (1983) in which

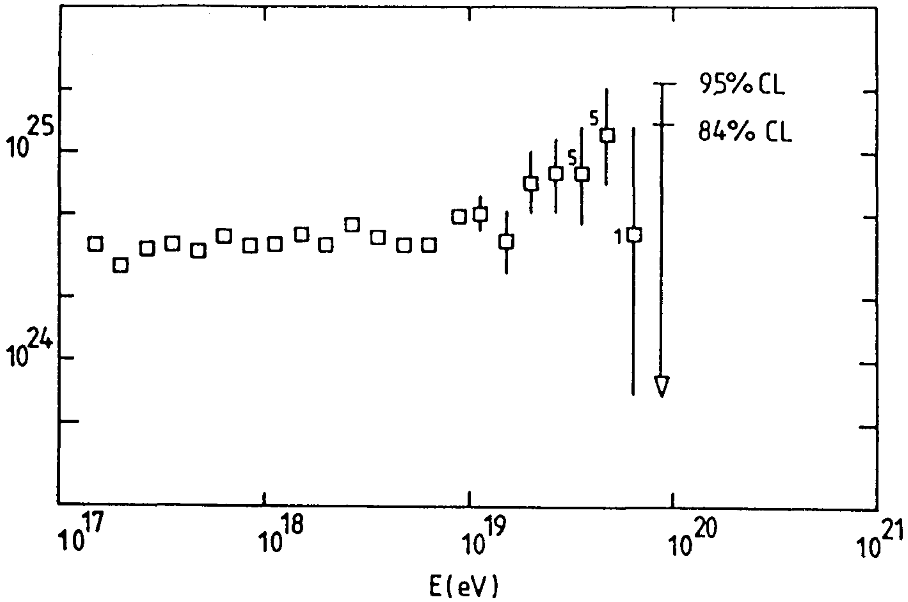


Figure 15: Differential energy spectrum measured by the Fly's Eye group (Baltrusaitis et al 1985a). The 68% confidence bands are calculated following Regener (1951).

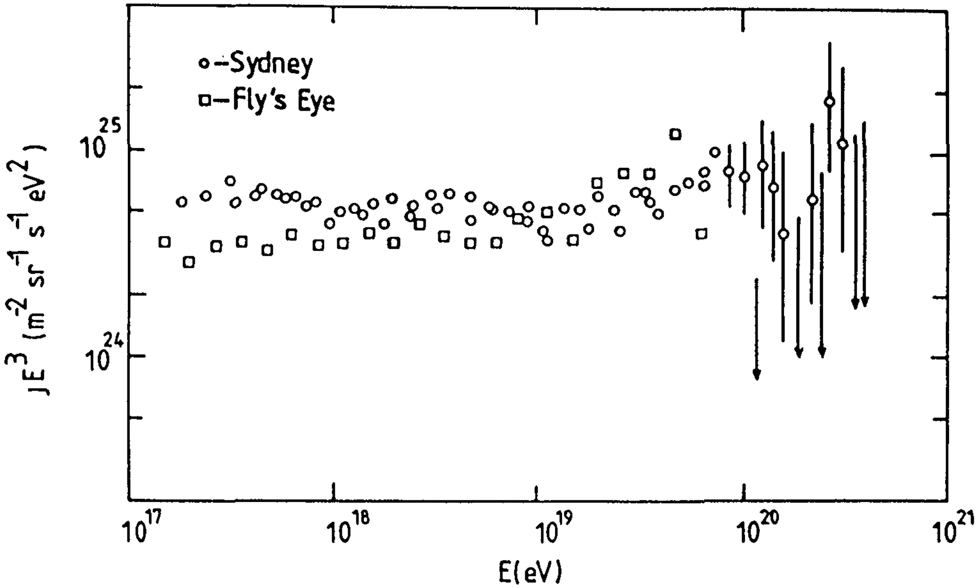


Figure 16: Comparison of the Fly's Eye (Baltrusaitis et al 1985a) with the Sydney spectrum (1985a). The latter has been calculated from N_μ using the calibration of Diminstein et al (1983).

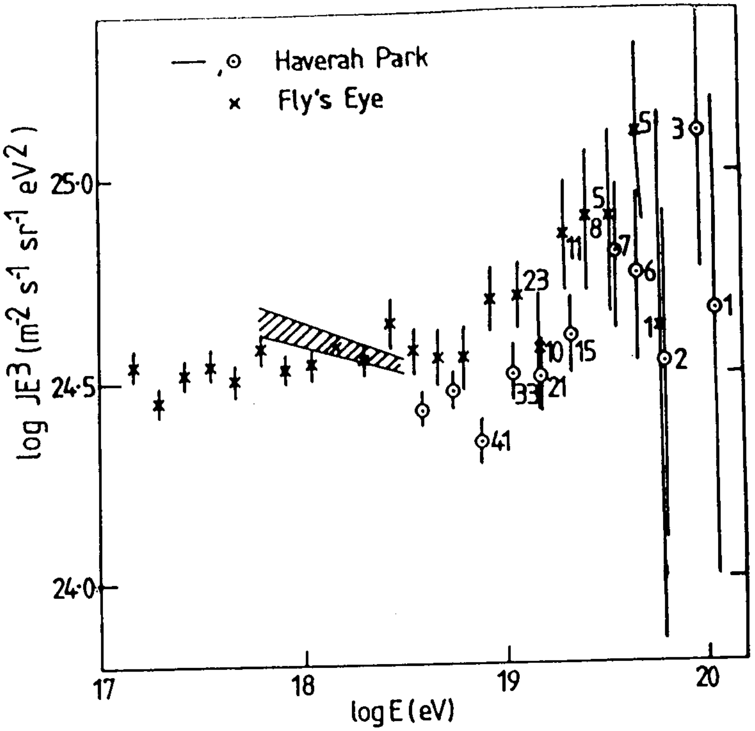


Figure 17: Comparison of Fly's Eye and Haverah Park spectra (OG 5.1-3).

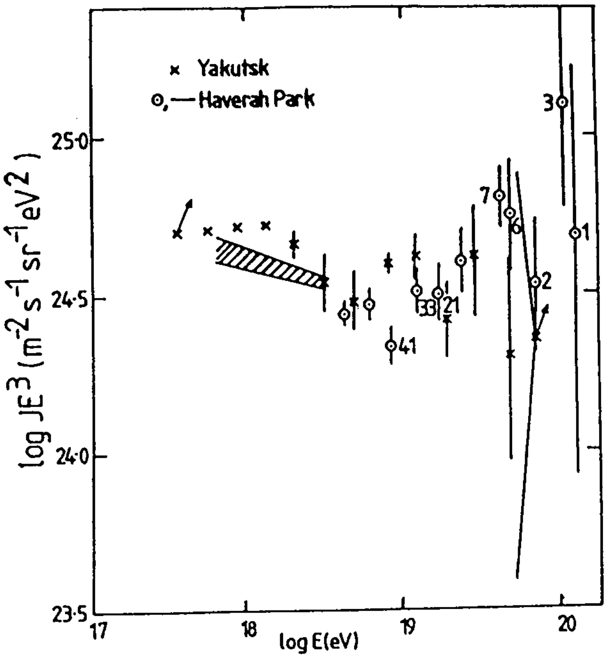


Figure 18: Comparison of Haverah Park and Yakutsk spectra. The arrows on the extreme Yakutsk points indicate the shift caused by their revised energy calibration (OG 5.1-7).

the scintillator density at 600 m, S(600), from the shower axis was related to the primary energy by calorimetric methods via the relation

$$E = (4.1 \pm 1.5) \times 10^{17}.S(600)^{0\cdot 96}\ \text{eV}.$$

At this meeting (OG 5.1-7) the Yakutsk group did not present a differential energy spectrum but note that a reassessment of the atmospheric transparency requires the E/S(600) relation to be revised to $E = (5.0 \pm 1.4).10^{17}\ S(600)^{0\cdot 96}$ thus increasing the primary energy calculated for each event by about 22%. The magnitude of this shift is shown in Figure 18; the discrepancy between the two measurements is increased near 10^{18} eV.

It is clear from examination of Figures 15-18 that it may be a long time before the shape of the spectrum above 10^{19} eV is agreed and it is certainly premature to discuss the existence or otherwise of the 'bump' discussed by Hill and Schramm (1985). The present position can be summarised as follows:-

1. The Haverah Park, Sydney and Volcano Ranch groups claim that the spectrum is flatter above 1 or 2×10^{19} eV than below. The joint total of events believed to be 10^{20} eV is now 17.

2. The Yakutsk group, who have performed a careful calorimetric calibration of their experiment, find some evidence for a steepening of the spectrum above $\sim 4 \times 10^{19}$ eV. They point out that their calibration has only been checked to about 2×10^{19} eV. However, it appears to agree well with the Haverah Park and Volcano Ranch conversions at least to 5×10^{19} eV (Bower et al 1983).

3. The Fly's Eye measurements are consistent with a flat spectrum from 10^{17} to 5×10^{19} eV.

4. There are events in Haverah Park, Sydney and Volcano Ranch data which are claimed to have energies well beyond the Greisen/Zatsepin cut-off. Extensive details of the Volcano Ranch and Haverah Park events have been published (Wada 1980) and their energy assignments are thought to be secure. Independent assessment of these claims - perhaps by a non-EAS person? - is highly desirable.

5. The best estimate of the integral intensity at 10^{20} eV is

$$I(>10^{20}\ \text{eV}) = \left(3^{+2}_{-1}\right) \times 10^{-16}\ \text{m}^{-2}\ \text{s}^{-1}\text{sr}^{-1}$$

$$\text{or} \simeq 1\ \text{km}^{-2}\ \text{sr}^{-1}\ \text{century}^{-1}.$$

6. Anisotropy of cosmic rays $> 10^{19}$ eV. Apart from the 'μ-rich anisotropy discussed above there has been no important change in our knowledge of cosmic ray arrival directions since the last conference, with one major exception. The Sydney group (Horton et al 1985b) have finalised their arrival direction study of cosmic rays above 5.10^{17} eV as seen in the Southern Hemisphere. This important work awaits detailed examination but there is one immediate and striking fact within their paper which

relates to the question of anisotropy of cosmic rays > 4×10^{19} eV as seen from the Northern Hemisphere. Data from Haverah Park and Volcano Ranch, when combined, yield a first harmonic amplitude above 4×10^{19} eV, based on 43 events, of (54 ± 22)% at $\theta = (190 \pm 23)^{\circ}$RA (chance probability = 0.043). Because the direction of the excess lies close to the centre of the local supercluster, which may well provide an enhancement of the cosmic ray intensity above this energy (e.g. Strong et al 1974), there has been speculation that this anisotropy is real. There are 19 Sydney events with $E > 4 \times 10^{19}$ eV and $\delta > 0^{\circ}$; for these the 1st harmonic in right ascension is represented by $a_1 = (45 \pm 32)\%$ and $\theta_1 = (134 \pm 40)^{\circ}$RA. The joint Haverah Park, Sydney, Volcano Ranch harmonic is $a_1 = (47 \pm 18)\%$, $\theta_1 = 175 \pm 22^{\circ}$ and $p = 0.033$. The three largest Sydney events which have $\delta > 0^{\circ}$ all arrive from close to the North Galactic Pole and the very largest event in Sydney listing has $\alpha = 188^{\circ}$, $\delta = 32^{\circ}$. These 3 events are plotted in Figure 19 together with the 43 events from Haverah Park and Volcano Ranch. This is a tantalising result but as the Volcano Ranch and Sydney experiments are now closed down, and little increase in the Haverah Park data set is to be expected, confirmation or otherwise must come from the Fly's Eye experiment and from the new giant array being developed at Akeno (OG 9.4-8).

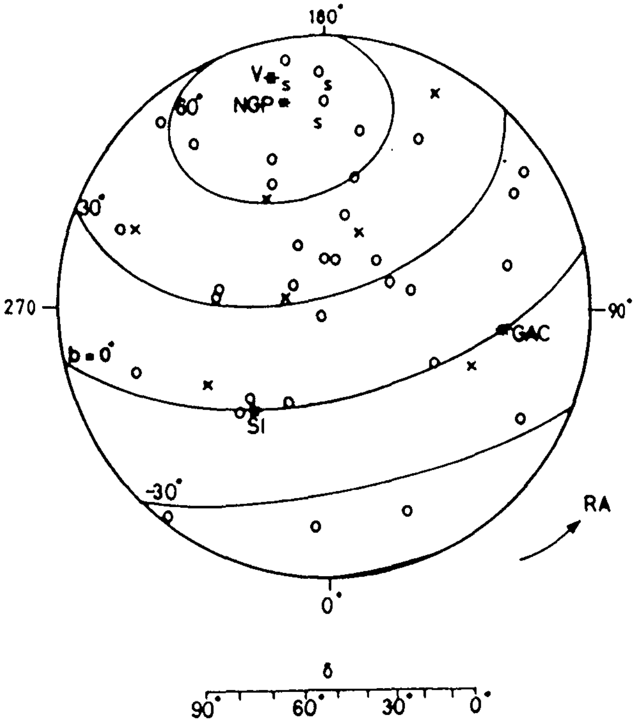


Figure 19: Events from Haverah Park (O), Volcano Ranch (X) and Sydney (S) above 4×10^{19} eV and with declination >0°. Only the 3 largest Sydney events in this category have been plotted.

There is no evidence from the Northern or Southern Hemisphere for any clustering near the Galactic Plane. If the 4×10^{19} eV anisotropy is strengthened through future studies and if the particles at the highest energy really are protons then the accelerators of these particles must surely lie in some of the more unusual objects within the local supercluster.

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References to pre-conference papers and pre-prints
ICRC ≡ International Cosmic Ray Conference

B.S. Acharya et al 1983 Proc. 18th ICRC (Bangalore) 11, 334.
V.V. Alexeenko et al 1984 Izv. Akad. Nauk SSSR Ser. Phys. 48, 2126.
V.V. Alexeenko & G. Navarra 1985 Lettre al Nuovo Cimento 42, 321.
K.M.V. Apparao 1984 Ap. J. 287, 338.
R.M. Baltrusaitis et al 1985 Ap. J. Lett. 293, L69.
R.M. Baltrusaitis et al 1985a Phys. Rev. Lett. 45, 1875.
C.L. Bhat, T. Kifune & A.W. Wolfendale 1985 submitted to Astron. Astrophys.
P.R. Blake et al 1975 Proc. 14th ICRC (Munich) 8, 2768.
J.M. Bonnet-Bidaud and M. van der Klis 1981 Astron. Astrophys. 101, 299.
J. Boone et al 1984 Ap. J. 285, 264.
A.J. Bower et al 1983 J. Phys. G 9, L53.
R. Buccheri et al 1985 Nature 316, 131.
T.H. Burnett et al 1982 in Workshop on Very High Energy Interactions, University of Pennsylvania 1982, p.220.
M.F. Cawley et al 1985 Ap. J. (in the press).
P.M. Chadwick et al 1985 submitted to Nature.
R.W. Clay, P.R. Gerhardy & D.F. Liebing 1984 Aust. J. Phys. 37, 91.
G. Cocconi 1959 Proc. 6th ICRC (Moscow) II, 309.
J.M. Dickey 1984 Ap. J. Lett. 273, L71.
O.S. Diminstein et al 1983 Proc. 18th ICRC (Bangalore) 6, 118.
J.C. Dowthwaite et al 1984a Ap. J. Lett. 286, L35.
J.C. Dowthwaite et al 1984b Astron. Astrophys. 136, L14.
J.C. Dowthwaite et al 1984c Nature 309, 691.
T. Dzikowski et al 1981 Proc. 17th ICRC (Paris) 1, 8.
N.N. Efimov & V.F. Sokurov 1983 Proc. 18th ICRC (Bangalore) 2, 123.
V.P. Fomin et al 1981 Proc. 17th ICRC (Paris) 1, 28.
W. Galbraith & J.V. Jelley 1953 Nature 171, 349.
A.I. Gibson et al 1982 Proc. Int. Workshop on VHE γ-ray astronomy Ootacamund, India, p.97.
P. Grieder 1983 Proc. 18th ICRC (Bangalore) 11, 323.
J. Grindlay et al 1975a Ap. J. 201, 82.
J. Grindlay et al 1975b Ap. J. Lett. 197, L9.
N.L. Grigorov et al 1971 Proc. 12th ICRC (Hobart) 5, 1746.
T. Hara et al 1983 Proc. 18th ICRC (Bangalore) 9, 198.
H. Hasegawa et al 1961 Proc. 7th ICRC (Kyoto) 3, 86.
C.T. Hill and D.N. Schramm 1985 Phys. Rev. D 31, 564.
A.M. Hillas 1984 Nature 312, 50.
A.M. Hillas 1984a Proc. of XIXth Recontre de Moriond, La Plagne, France.
L. Horton et al 1985a Sydney University pre-print, 'The Cosmic Ray Energy Spectrum above 10^{17} eV'.
L. Horton et al 1985b Sydney University pre-print, 'The Arrival Directions of Cosmic Rays above 10^{17} eV'.
E. Juliusson 1975 Proc. 14th ICRC (Munich) 8, 2689.
K. Kamata 1977 Proc. 15th ICRC (Plovdiv) 12, 102.
T. Kifune et al 1985a submitted to J. Phys. G.
T. Kifune, J. Wdowczyk & A.W. Wolfendale 1985b submitted to J. Phys. G.
M. van der Klis & J.M. Bonnet-Bidaud 1981 Astron. Astrophys. Lett. 95,L5.
A.N. Kvashnin et al 1983 Proc. 18th ICRC (Bangalore) 11, 394.
R.C. Lamb et al 1977 Ap. J. Lett. 212, L63.
R.C. Lamb & T.C. Weekes 1985 submitted to Nature.
J. Linsley 1981 Proc. 17th ICRC (Paris) 2, 141.
J. Linsley 1983 Proc. 18th ICRC (Bangalore) 12, 135.

J. Linsley & A.A. Watson 1977 Proc. 15th ICRC (Plovdiv) 12, 203.
J. Linsley & A.A. Watson 1981 Phys. Rev. Lett. 46, 459.
J. Lloyd-Evans et al 1983 Nature 305, 784.
M.L. Marshak et al 1985 Phys. Rev. Lett. 54, 2079.
C.A. Meegan, G.F. Fishman & R.C. Haynes 1979 Ap. J. Lett. 234, L123.
M. Nagano et al 1984 J. Phys. G 10, 1295.
Yu. I. Nesphor et al 1979 Astro. Sp. Sci. 61, 349.
S.I. Nikolskii & J.N. Stamenov 1983 Proc. 18th ICRC (Bangalore) 2, 115.
D.R. Parsignault et al 1976 Ap. J. Lett. 209, L73.
W. Priedhorsky & J. Terrell 1986 Ap. J. (1 Feb. issue).
R.J. Protheroe, R.W. Clay & P.R. Gerhardy 1984 Ap. J. Lett. 280, L47.
R.J. Protheroe & R.W. Clay 1985 Nature 315, 205.
V.H. Regener 1951 Phys. Rev. 84, 161.
C. Reppin et al 1979 Ap. J. 234, 329.
M. Samorski & W. Stamm 1983a Ap. J. Lett. 268, L17.
M. Samorski & W. Stamm 1983b Proc. 18th ICRC (Bangalore) 11, 244.
F.W. Stecker, A.K. Harding & J.J. Barnard 1985 Nature 316, 418.
A.A. Stepanyan et al 1972 Nature Phys. Sci. 239, 40.
A.W. Strong, J. Wdowczyk & A.W. Wolfendale 1974 J. Phys. G 7, 1767.
I.V. Vaselev et al 1983 'Cosmic Rays with Energy $> 10^{17}$ eV', Yakutsk Branch of Academy of Science USSR, EDK 537.591, p.19.
B.M. Vladimirsky et al 1973 Proc. 13th ICRC (Denver) 1, 456.
M. Wada (Editor) 1980 World Data Catalogue of Highest Energy Cosmic Ray Showers N^{o} 1: published by World Data Center for Cosmic Rays.
R. Walker & A.A. Watson 1983 Proc. 18th ICRC (Bangalore) 6, 114.
A.A. Watson 1984 Adv. Space Res. Vol. 4, 35.
J. Wdowczyk & A.W. Wolfendale 1983 Nature 305, 609.
J. Wdowczyk 1985 Int. School of Astrophysics, Erice (in press, D. Reidel).
T.C. Weekes et al 1981 Astron. Astrophys. 104, L4.
T.C. Weekes 1982 Proc. Int. Workshop on VHE γ-ray astronomy, Ootacamund, India, p.272.
R. Willingale, A.R. King & K.A. Pounds 1985 Mon. Not, R. Astr. Soc. 215, 295.
R.D. Wills et al 1982 Nature 296, 723.
G.B. Yodh et al 1984 Phys. Rev. D 29, 892.