TeV and PeV radiations from the Crab

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The Crab nebula, which is the remnant of a supernova explosion that occurred in 1054, is one of the most fascinating objects in the sky that is extensively studied in all the bands of the electromagnetic spectrum. The source of energy from this object is the fast spinning central magnetized neutron star. The environment is most suitable for it to be a source of very high energy cosmic rays accelerated in the magnetosphere of the pulsar. Detection of very high energy gamma rays from this object is the only sure way to confirm. In the last decade, intense efforts have been on by several groups to detect these very high energy gamma rays. Due to a recent technical breakthrough, the Crab nebula is now confirmed to be a steady gamma-ray emitter in the TeV energy region. The evidence for a steady but pulsed TeV and PeV emission from the pulsar is not so firm. However, TeV and PeV emissions from the pulsar appear to be transient in nature. A recent simultaneous observation of a PeV energy burst by four different groups has features which have important implications for the acceleration of particles, production of gamma rays and their behaviour at very high energies.

The present status of TeV and PeV observations on the Crab and the models proposed for gamma-ray emission at these energies are reviewed and the anomalies in the steady, pulsed and transient modes highlighted to focus attention on the types of future observations and modelling that are required.

ACCORDING to the chronicles left by the Royal Astronomer, Yang-Wei-Te, of the Sung Dynasty in China, "on a Chi-Chou day of the 5th month of the first year of the Chi-Ho period, a 'guest star' suddenly appeared at the southeast of Thien-Kaun measuring several inches". The star was visible for 23 days during day time and was as bright as Venus and could be seen for 650 nights. This celestial event according to Julian calendar happened on the 4 July 1054 AD in the constellation Taurus and has been identified with the explosion of a star, resulting in a supernova remnant, the Crab nebula, which with the present day telescopes is seen as a hot web of gas with bright reddish filaments. Optical observations, taken a decade apart, have revealed the expanding nature of the hot mass with rather high velocities. It has now been estimated that the supernova reached a maximum visual magnitude of -6.5 to -7 and with the distance estimate of 2 kiloparsecs the absolute magnitude must have been at least -16.5. One of the most powerful radio sources, Taurus A, is identified with the nebula.

The radiation from the nebula is polarized in the optical, radio and even in the 3.15-cm radio wave region. Schklovsky[1] pointed out in the early fifties that the high degree of optical polarization could be accounted for by synchrotron process requiring the presence of very high energy ($> 10^{12}$ eV) electrons gyrating round the magnetic fields ($\sim 10^{-4}$ G) in the filaments. In 1960 Cocconi[2] suggested that since electrons of such high energy cannot arise from nuclear-decay processes, a mechanism of acceleration of particles to high energies must be operative in the nebula. If such a mechanism was indeed present, there was no reason why protons could not be accelerated to high energies too. Presence of such high-energy protons meant that these particles in their nuclear collisions with the filamentary matter could produce charged and neutral pions. Large-scale efforts to look for high-energy (hundreds of GeV) gamma rays from the decay of neutral pions were mounted in the late fifties. The survey also included other supernova remnants. Two methods were employed for this purpose depending upon the energy of the gamma rays of interest. The first method, which has come to be known as the Air Cerenkov Technique (ACT), used the pool of Cerenkov photons produced by the cascade electrons in traversing the atmosphere. The pool of light was collected by a system of search light mirrors mounted on orientation platforms. These could be pointed in the direction of any suspected source and made to follow the source for several hours; the photomultipliers at the foci of the mirrors recorded the intensity of Cerenkov radiation. The requirement of coincident pulses in several mirrors, aligned parallel to each other, reduced the background counting rates, essentially due to star light. This method is used in the TeV (10^{12} eV) energy region, where the number of cascade particles reaching the observation level is too small to be detected. In the second method used at PeV (10^{15} eV) energies, where the number of cascade particles reaching the observation level is large enough to be recorded, extensive air shower (EAS) arrays are employed. In these arrays, a large number of unshielded plastic scintillators are set up over a large area for recording the densities of shower particles, from which the energy of the primary particle is estimated. The arrival times of the shower front at different detectors enable the determination of the arrival direction and large area shielded counters record the associated muons. The mu-poor or mu-less criterion for showers preferentially select γ-ray-induced showers and help in reducing the background from the dominant hadron-induced cosmic-ray showers. While the second method has the advantage that the array can operate day and night and many sources can be observed at the same time, the first one has the disadvantage that the operation is confined only to dark moonless, cloudless nights and only one source can be observed at a time. The EAS method was first used by the BASJE group[3] who set up a specially designed array at the high altitude station in Bolivia. The Lebedev group[4] first used the ACT method at Pamir.

The two methods have undergone considerable sophistication in the last several decades. Typical modern day arrays of each type are shown in Figures 1 and 2.

It turned out that both types of experiments, having operated for several years in the early sixties, yielded negative results. Only upper limits could be set on the flux of high energy photons from supernova remnants. Chudakov *et al.*[4] set an upper limit of 5×10^{-11} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for gamma rays of energy > 5 TeV, almost three orders of magnitude smaller than that suggested by Cocconi.

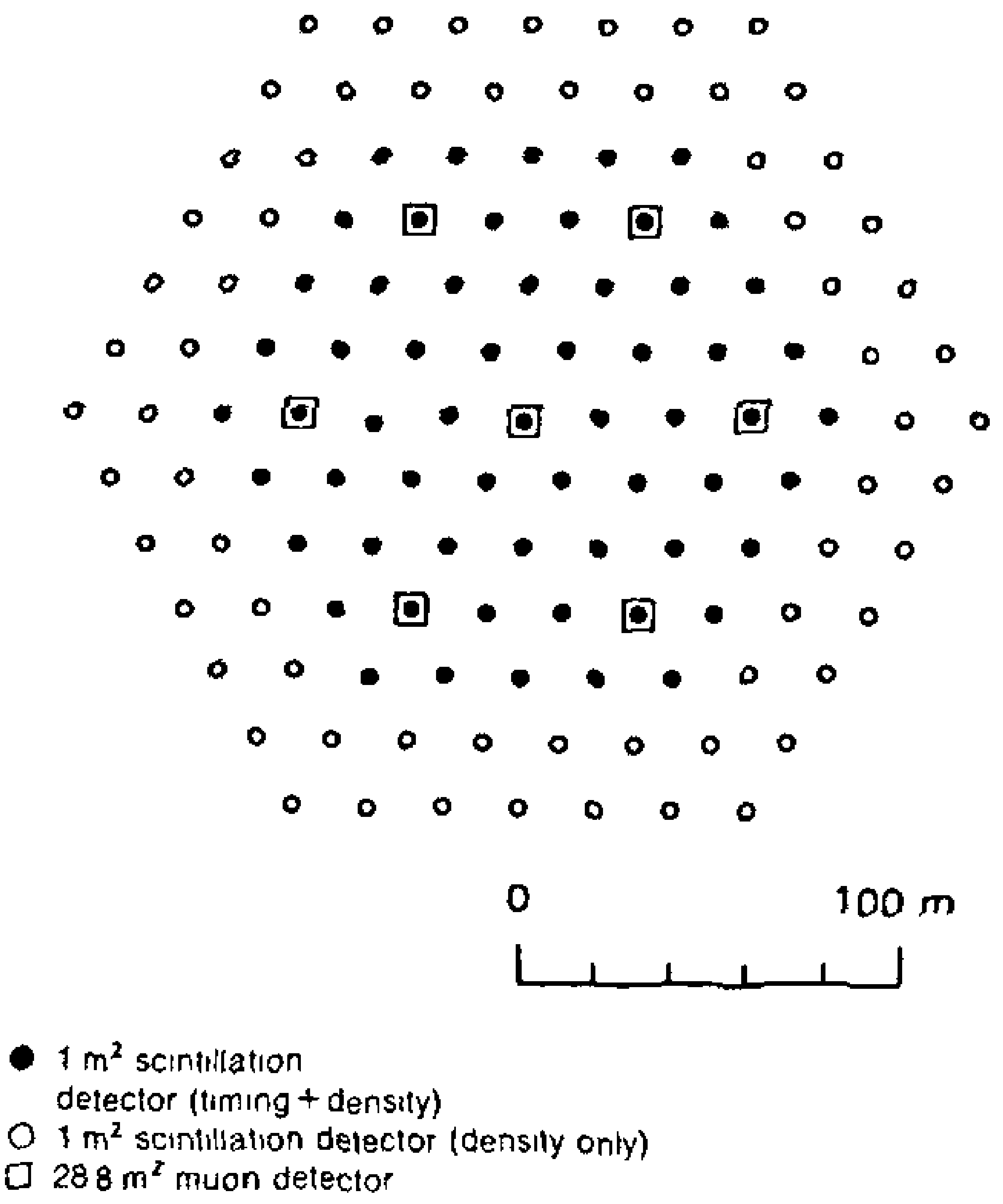

Figure 1. A typical air shower array for PeV gamma-ray observations being operated at Kolar Gold Fields (KGF), India. The total number of particles, called shower size, and hence the energy of the primary particle, are estimated from the number of shower particles recorded in the density detectors shown as open circles. The arrival direction of the shower is obtained from the relative arrival times of the shower front recorded in the timing detectors shown as filled circles. The seven muon detectors, shown as squares, sample the muon component in the shower.

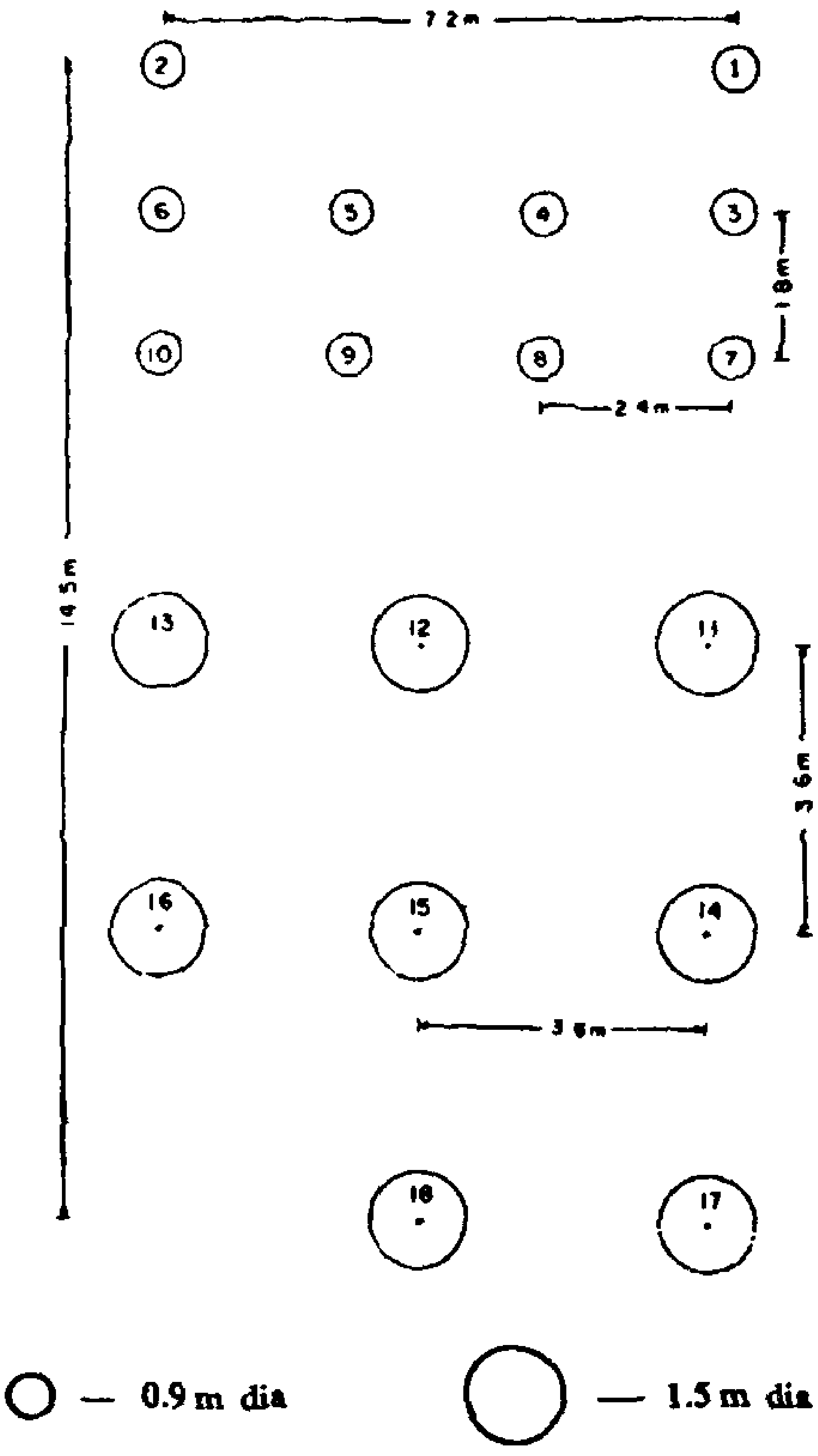

Figure 2. A typical array of parabolic mirrors for TeV gamma-ray studies at Ootacamund, India. Photomultipliers located at the foci of the mirrors collect the Cerenkov light emitted by the shower particles in the atmosphere. The night sky background is reduced by operating them in coincidence. The telescope is pointed at the source under observation with a typical aperture of about a degree. The cosmic ray background is obtained by pointing the telescope off the source, but in the same region of local zenith angle.

In 1963 a new development took place and the Crab nebula came back to the prime focus of research efforts, from which position it has not moved out, but has continued to provide many surprises of fundamental interest to both physicists and astrophysicists. While the first soft X-ray source discovered in a rocket experiment was Sco X-1, the first hard X-ray source discovered in a balloon experiment was Tau X-1, identified with the Crab nebula. The very first reaction to finding an X-ray source in the Crab was that the X-rays were coming from the neighbourhood of the neutron star that was supposed to be left behind in the supernova explosion. H. Y. Chiu indicated this possibility at the first Texas Symposium held in December 1963. However, the rocket experiment carried out by the NRL group (prompted by Schklovsky) in which the occultation of the Crab nebula by the moon was utilized for measuring the size of the X-ray source, disproved the neutron star hypothesis since the size found was much too large.

However, within a few years a major surprise was in store. In 1968 the fastest radio pulsar with a pulsation rate of 30 per second, turned out to be right in the centre of the Crab nebula and was soon identified using the stroboscopic technique for the pulsing optical signal, to be the remnant star of the supernova explosion and the neutron star hypothesis fitted all the observations. It was estimated that the spinning neutron star would be surrounded by a dipole magnetic field of $\sim 10^{12}$ G. Such a scenario was what was just necessary for the theorists to propose several possible ways in which particles could be accelerated to high energies. In these models the spinning neutron star was the central engine for energy generation and replenishment of what was being removed from the nebula in the form of radiations in the various bands of the electromagnetic spectrum. Pulsation at the rate of 30 per second was recorded in IR, optical, UV and X-ray regions and also in MeV gamma ray energy region by satellite experiments. All this led to a revival of interest in further observations on the Crab nebula in the TeV and PeV energy regions as well.

There are some excellent reviews[5–11] on the subject of TeV and PeV gamma ray astronomy, in which the Crab is covered. In this article, we review the current observational status of the high energy Crab and examine to what extent the models proposed for high energy gamma-ray production fit the experimental observations. We discuss some of the problems raised by the new observations in understanding the high energy astrophysical phenomena.

Steady TeV and PeV emission from the Crab nebula

In 1965 Gould[12] proposed that high energy electrons, whose source was not specified, would Compton scatter on the synchrotron radiation they emit in the nebular magnetic field and boost them to high energies. According to this Compton-synchrotron model, the flux of TeV energy photons was estimated to be $\sim 10^{-10}$ cm^{-2} s^{-1}, assuming an equipartition magnetic field of 10^{-4} G. This model was subsequently refined by others[13,14] using the updated parameters of the nebula.

Several groups[15–17] attempted without success to detect this flux and set only upper limits. The first positive detection of TeV energy gamma rays from the nebula was reported by Fazio *et al.*[18] (Smithsonian group) in 1972 after three years of observation. From 150 h of observations they detected a signal at 3σ level and estimated a flux of $(5.7 \pm 1.8) \times 10^{-11}$ photons cm^{-2} s^{-1} of energy above 0.14 TeV. They also presented some evidence for time variation correlated with glitches in the pulsar. Mukanov *et al.*[19] using the drift-scan method, in which the source was allowed to drift across the field of view of the telescope, at Tien Shan obtained a flux of $(5.7 \pm 1.3) \times 10^{-11}$ photons cm^{-2} s^{-1} at energy > 2 TeV.

A very important development has taken place recently in detecting steady emission of TeV gamma rays from the Crab nebula. The Whipple group[20–23], using the 'imaging' technique, developed over a period of time, to select gamma-ray-like events has succeeded in detecting a significant flux with their 10-m imaging camera. The technique makes use of the fact that the angular distribution of the Cerenkov-emitting electrons, and hence of the photons themselves, is narrower in gamma-ray cascades compared to cosmic ray background proton-induced showers. In the pure electromagnetic cascades the spread is determined only by the Coulomb scattering of the electrons in the cascade whereas in proton-induced showers the opening angles of π^0 mesons produced in the nuclear cascade dominate and broaden the distribution. They used the Monte Carlo simulations of gamma-ray and cosmic-ray showers developed by Hillas[24] to define a quantitative criterion (Azwidth) to differentiate gamma-ray showers from hadron showers with a high efficiency. In the early eighties, even with a crude selection of gamma-ray events with narrow Cerenkov images, they obtained a 5σ signal[20] and reported a flux of 6×10^{-11} photons cm^{-2} s^{-1} at $E > 0.4$ TeV. Later they refined this technique and reduced the cosmic-ray background by 97% using small values of the 'azwidth' parameter, which selects events not only with narrow angular width but also those arriving in the central part of the field of view. With this technique they detected[21] the source at a level of 9σ during 1986–88, which was the most significant signal from Crab at that time. These observations yielded a flux of 1.8×10^{-11} photons cm^{-2} s^{-1} at $E > 0.7$ TeV, with a factor of 1.5 uncertainty in both flux and energy estimates. They also found that the emission is constant within statistics over this period and indicated the possibility that the Crab nebula might be a 'standard candle' for TeV gamma-ray astronomy.

The Whipple collaboration have in recent years further improved their camera with a smaller pixel size, a lower energy threshold and a still better discrimination against cosmic-ray showers and have obtained a 20 σ signal during 1988-89 (ref. 23), which gave a flux of 7×10^{-11} photons $cm^{-2}s^{-1}$ at $E>0.4$ TeV. With such a strong signal and the measured pulse height spectrum, they have been able to estimate the source energy spectrum[23]. The differential energy spectrum is found to be $N(E)\,dE=2.5\times10^{-10}\,(E/0.4)^{-2.4\pm0.3}\,dE$ photons $cm^{-2}s^{-1}TeV^{-1}$ with E in TeV. The virtue of obtaining the energy spectrum from a single experiment cannot be overstated. It obviates the uncertainties in energy thresholds and fluxes of widely different experiments carried out in different locations and at different times. They found that the monthly average fluxes are constant over this entire period, confirming that Crab nebula is indeed a 'standard candle' in the TeV energy region.

Several other groups[25-27], using a similar technique, have also detected steady emission and confirmed the nebula to be a steady TeV source. The University of Michigan group[25] applying selection criteria, similar to the earlier crude criteria of the Whipple group, on their data collected during November–December 1988 obtained a 5.8 σ signal and gave a flux of 1.8×10^{-10} photons $cm^{-2}\ s^{-1}$ at $E>0.2$ TeV. The University of California Collaboration[26,27], using a slightly different technique of pulse shape discrimination and drift-scan method, have also detected the signal at a level of 4.2 σ and reported a flux of $(2.5\pm1.3)\times10^{-11}$ photons $cm^{-2}\ s^{-1}$ at $E>0.6$ TeV.

In the PeV energy region, where the EAS method is used, the estimate of background is easier because the background is automatically monitored all the time. The Lodz group[28] found a 5.4 σ excess at >10 PeV from the direction of Crab, summing up the results of a seven-year period from 1975 to 1982. Due to poor angular resolution the excess was seen over a large angular bin around Crab (37.5° in right ascension and 10° in declination); so it is not clear if all the excess is from Crab. The deduced flux was 2×10^{-13} photons $cm^{-2}\ s^{-1}$ at $E>10$ PeV. The muon content of the showers from Crab was not significantly smaller than that in the cosmic-ray background showers. However, the errors on the muon measurements were such that no conclusions could be drawn about the nature of the primaries. For example, the muon content, relative to that in cosmic-ray showers, in the data sample collected during 1968–75 was found to be[29] 0.60 ± 0.12, which was consistent with both gamma-ray and proton-primary hypotheses within 3 σ. The total data sample[28] collected during 1968–82 seems to show somewhat higher muon content. The Tien Shan group[30] also detected the signal from Crab during 1974–82 with their EAS array at the Tien Shan mountain station, but only in muon-poor showers of somewhat lower primary energy. They also used a large angular bin of 15° × 15° around Crab. The fluxes reported by them are $(2.8\pm0.8)\times10^{-13}$ and $(1.9\pm0.7)\times10^{-13}$ photons $cm^{-2}s^{-1}$ at energies greater than 350 and 550 TeV respectively. The only other positive detection from Crab was during an episode of about six hours on 9 December 1980, reported by the Fly's eye group[31]. While they detected a 3 σ signal at $E>1$ PeV on that day, they did not see any excess in the runs in February of the following year. The reported fluxes during the 9 December episode were $(8.2\pm3.1)\times10^{-12}$, $(2.1\pm0.7)\times10^{-12}$ and $(3.3\pm1.3)\times10^{-13}$ photons $cm^{-2}\ s^{-1}$ at $E>0.3$, 1 and 3 PeV respectively.

The Akeno group[32], however, did not find any excess at $E>2$ PeV within 10° × 10° bin around Crab either in normal or mu-poor showers in their data collected during 1978–81. Their upper limit is an order of magnitude lower than the Lodz flux. The Haverah Park group[7] also did not find any excess in the same energy region during 1979–84. Their 95% CL upper limits are 1.5×10^{-13} and 1.5×10^{-15} photons $cm^{-2}\ s^{-1}$ at $E>1$ and 10 PeV respectively. Their upper limit at 10 PeV is two orders of magnitude smaller than the finite flux reported by the Lodz group. No information on the muon content is available from this experiment.

The Durham group[33] also looked for excess in a 15° × 15° bin around Crab with their widely spread Cerenkov array at Dugway operated during 1977–80. Failing to find any excess, they set 3 σ upper limits of 1.7×10^{-13} and 6.6×10^{-14} photons $cm^{-2}\ s^{-1}$ at energies >9 and 30 PeV respectively. Their limit at the lower energy is, however, consistent with the Lodz flux.

In all these PeV observations the absolute or relative time keeping was not accurate enough to subject the data for pulsar analysis. So, one cannot rule out the possibility that at least part of the emission in the reported positive detections is pulsed.

In recent years, many groups have been operating EAS arrays optimized for PeV gamma-ray observations with good angular resolution and equipped with large area muon detectors. None of them[34-39] has succeeded in detecting a finite steady flux from the Nebula.

The fluxes and the limits from the various observations over the energy range 10^{-1} to 10^5 TeV are listed in Table 1 and plotted as a function of energy in Figure 3 and the energy spectra predicted by different theoretical models are also shown. The spectrum observed by the Whipple collaboration[23] is shown as the solid box, with the dashed lines indicating extrapolation to higher energies. The thick line marked (a) is the spectrum predicted for an ambient magnetic field of 3×10^{-4} G by the Compton-synchrotron model referred to earlier, taken from ref. 21. The recent observations, including the Whipple spectrum, based on more accurate energy and flux estimates agree very well with this model—in particular the slope of the spectrum. The disagreement with the earlier observations of the Smithsonian group[18] and the Tien Shan group[19] may

Table 1. TeV and PeV observations from Crab nebula

Ref.	Epoch	Threshold energy (TeV)	Significance (σs)	Flux (Photons cm^{-2} s^{-1})	Remarks
Positive detections					
18	1969–72	0.14	3.0	$(5.7 \pm 1.8) \times 10^{-11}$	
30	1974–82	350	4.0	$(2.8 \pm 0.8) \times 10^{-13}$	μ-poor
		550	4.2	$(1.9 \pm 0.7) \times 10^{-13}$	μ-poor
28	1975–82	10,000	5.0	2×10^{-13}	37.5° × 10°
19	1979–81	2	4.4	$(5.7 \pm 1.3) \times 10^{-11}$	
31	1980	300	2.7	$(8.2 \pm 3.1) \times 10^{-12}$	
		1,000	3.1	$(2.1 \pm 0.7) \times 10^{-12}$	
		3,000	2.5	$(3.3 \pm 1.3) \times 10^{-13}$	
20	1983–85	0.4	5.2	6×10^{-11}	
21	1986–88	0.7	9.0	1.8×10^{-11}	
26	1987	0.4 ± 0.2	4.3	$(6.3 \pm 1.5) \times 10^{-11}$	
27	1987	0.6 ± 0.3	4.2	$(2.5 \pm 1.3) \times 10^{-11}$	
25	1988–89	0.2	5.8	1.8×10^{-10}	
22	1988–89	0.4	15.3	7×10^{-11}	
23	1988–89	0.4–4.0	20.0	$(7.1 \pm 1.5) \times 10^{-11}$ $(E/0.4)^{-(1.4 \pm 0.3)}$	
Upper limits					
4	1960–63	5		5×10^{-11}	
15	1963–64	27		1.3×10^{-11}	
16	1972–75	20		2×10^{-12}	
33	1977–80	9000		1.7×10^{-13}	
		30,000		6.6×10^{-14}	
7	1979–84	1000		1.5×10^{-13}	
		10,000		1.5×10^{-15}	
31	1981	1000		5×10^{-13}	
17	1981	1		3×10^{-11}	
34	1982–84	30		10^{-11}	
38	1984–87	200		7.7×10^{-13}	
36	1987–88	45		3.9×10^{-12}	
39	1987–89	40–70		9.9×10^{-13}	
37	1988–89	150		2.2×10^{-13}	
35	1988–89	270		2.3×10^{-13}	
		600		1.8×10^{-13}	
		1200		1.3×10^{-13}	
		270		1.2×10^{-14}	μ-poor
		600		5.8×10^{-15}	μ-poor
		1200		4.5×10^{-15}	μ-poor

be due to large uncertainties in these estimates, which are truly not reflected in the error bars. This model, however, does not agree with observations in the lower 100 MeV region[24]. Cheng *et al.*[40] proposed a model in which protons accelerated up to ~ 2000 TeV in the outer magnetospheric gap of the pulsar (as in an earlier model of Cheng *et al.*[41]) are stored for a long time in the nebula due to the ambient magnetic field and these protons interact with the ambient matter in the nebula and produce π° mesons, which then decay into gamma rays. The spectrum predicted by this model is shown as curve (b) in Figure 3. While this model predicts the right magnitude of fluxes, the spectral shape does not agree. In yet another model proposed by Kwok and Cheng[42] and referred to by Vacanti *et al.*[23], the relativistic electrons accelerated in the outer magnetosphere enter the nebula and Compton-scatter on the infra red photons they themselves produce by synchrotron mechanism and boost the photons to very high energies; these photons further cascade and produce TeV gamma rays which escape and are the ones that are detected in the experiments. Perhaps a combination of all these processes is responsible for the observed fluxes and spectral characteristics.

Recently De Jager and Harding[43] recalculated the Compton-synchrotron spectrum using a more detailed magnetic field structure in the nebula. They argue that the magnetic field increases with distance, r, as the wind sweeps up the field until equipartition is reached and falls off as $1/r$ thereafter. The only free parameter in their model is σ, which decides the partition between the particle and magnetic luminosity of the pulsar. They also use an electron energy spectrum derived as a function of r from the radio, optical and X-ray observations. Their results are shown as dotted curve in Figure 3. The best fit to the TeV observations is obtained with $\sigma = 0.001$. Their model also predicts correct fluxes in the 100 MeV region, but requires electrons of energy ~ 10^{16} eV in the nebula. They suggest that TeV electrons, escaping from the pulsar,

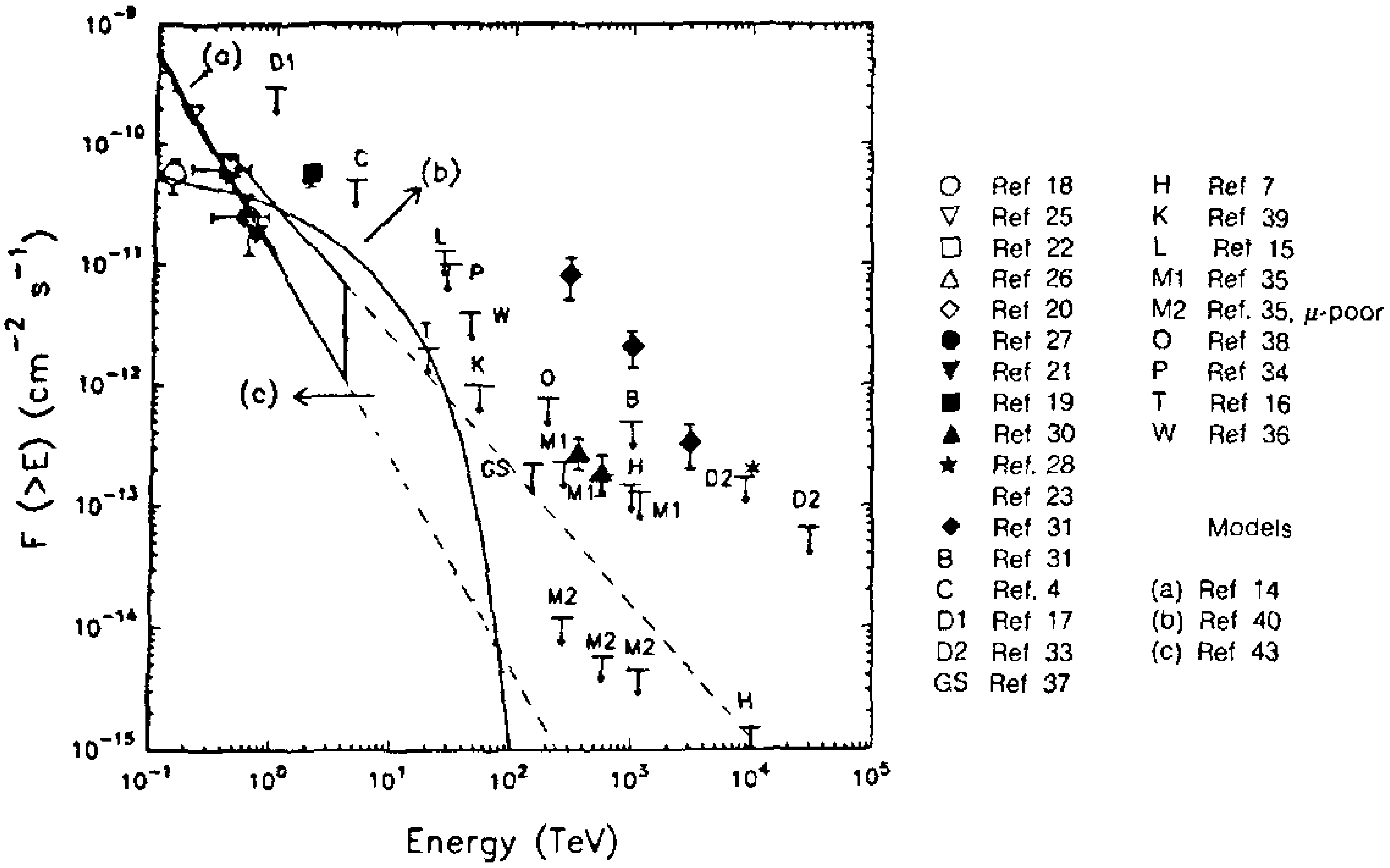

Figure 3. Energy spectrum of gamma rays from Crab nebula. The dashed lines are the extrapolations of the upper and lower 1 s limits of the observed Whipple spectrum. The thick line is the prediction of the Compton-synchrotron model of Grindlay and Hoffman[14]. The solid curve is the prediction of the hadronic model of Cheng *et al.*[40]. The dotted curve is due to the refined model of De Jager and Harding[43].

gain energy from shock acceleration in the nebula. Using the theory of parallel non-relativistic shocks, they estimate the maximum gain in energy to be 3×10^{15} eV. They suggest that observations in the PeV energy region and a spectral depression in the GeV region will give a measure of the magnetic field at the shock (smaller the field, larger the PeV flux) and the maximum gain in energy due to shock acceleration.

In the PeV energy region, all the upper limits are consistent with the extrapolation of the Whipple spectrum shown by dashed lines. The Fly's eye points (Boone *et al.*[31]) correspond to episodic emission lasting a few hours and is several orders of magnitude higher. The Tien Shan fluxes at a few hundred TeV (Kirov *et al.*[30]), based on mu-poor selection are also higher than the extrapolated spectrum. The upper limits for mu-poor showers given by the Utah–Michigan collaboration (Corbato *et al.*[35]), marked M2 in Figure 3, are however in complete disagreement with the Tien Shan results. There is no time overlap between the two experiments. Long term variability of the source on the scale of several years has to be invoked in order to reconcile these results. The most disturbing discrepancy in the PeV region is between the Lodz (Dzikowski *et al.*[28]) and the Haverah Park (Watson[7]) experiments which are contemporaneous. The finite flux of the Lodz group is about 100 times larger than the upper limit of the Haverah Park group. One way to understand the wide discrepancy is to assume that the Lodz flux is not from the Crab alone, but also forms part of general emission from the galactic plane. The Lodz group[44] found from the same data base, excess mu-poor showers within ±17.5° of the galactic plane. They constitute 1–2% of the cosmic-ray flux and so the gamma-ray flux from the galactic plane is about 2.3×10^{-14} photons cm^{-2} s^{-1} sr^{-1} at $E > 10$ PeV. Therefore the cosmic gamma-ray flux expected in the solid angle around Crab (37.5° × 10°) in the Lodz experiment is $\sim 2.6 \times 10^{-15}$ photons cm^{-2} s^{-1}, which is two orders of magnitude lower than the reported flux from Crab. The expected cosmic gamma-ray flux in the Haverah Park experiment (solid angle of 6° × 6°) is $\sim 2.5 \times 10^{-16}$ photons cm^{-2} s^{-1}, which is consistent with their upper limit of 1.5×10^{-15} photons cm^{-2} s^{-1} at $E > 10$ PeV. Thus it is difficult to understand the large flux seen in the Lodz experiment either in terms of flux from Crab or background gamma-ray flux.

The emission due to the Compton-synchrotron process does not extend to PeV energies because of severe energy losses of the electrons during acceleration. In the hadronic model of Cheng *et al.*[40] the spectrum extends beyond 10 TeV, but shows a sharp cut off around 100 TeV, even though, according to the model, protons could be accelerated up to $\sim 10^{17}$ eV in the pulsar outer magnetosphere and then confined in the nebula. This sharp cut off in the gamma-ray spectrum may be because they have used the scale-breaking model of Wdowczyk and Wolfendale[45] for hadronic interactions. In this interaction model scaling is violated in the fragmentation region also, because of which the π^0s cannot acquire high enough energies. There is evidence from recent accelerator data[46], however, that scaling is preserved in the fragmentation region at PeV energies. If this feature is included in the calculations of Cheng *et al.*, then perhaps it is possible to get higher fluxes in the PeV energy region. Also, if protons can be re-accelerated in the nebula due to shock mechanism, as are electrons in the model of De Jager and Harding, higher fluxes of PeV gamma rays can be expected.

TeV and PeV pulsed emission from the Crab pulsar

Soon after the discovery of pulsars, several groups[47–51] looked for TeV pulsed emission from the Crab pulsar. While some of them reported only upper limits[47,49], the first positive detection came from Grindlay[48] of the Smithsonian group. He used a technique[52], for the first time in the TeV region, to distinguish between gamma-ray and cosmic-ray showers. He used an assembly of three mirrors to collect the Cerenkov light produced by the shower particles. Two of the mirrors, located 70 m apart, were pointed but with a slight convergence between them along the direction of the Crab such that they collected the Cerenkov light produced by the particles at the shower maximum high in the atmosphere. The third mirror, also oriented in the direction of Crab, had a larger tilt and pointed to a region lower in the atmosphere to record the Cerenkov light emitted by muons, which penetrated to deeper levels. To select gamma-ray showers the third mirror was used in anticoincidence since gamma-ray showers were expected to have very low muon content. Using this technique, Grindlay detected 3.5 σ and 5.4 σ signals in the main and interpulse regions respectively. The flux estimated from these observations was $(1.25 \pm 0.6) \times 10^{-11}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at $E > 0.68$ TeV. This is the first time that a signal has been detected from the pulsar when gamma-ray-like events are selected.

In the TeV-energy region several groups have improved the sensitivity of their telescopes in recent years, by increasing the number of mirrors, and installed accurate clocks that enable analysis of the data for pulsed emission. The availability of contemporaneous ephemeris from radio observations by the Jodrell Bank Radio Observatory has been a vital input for pulsar analysis. This is necessary, especially in the case of Crab, since the period increases continuously with time and occasional glitches that produce sudden changes occur. While many of these observations[23,53–55] have led to negative results regarding steady pulsed emission, evidence for episodic pulsed emission lasting over several minutes to several days has been accumulating slowly. Some of these episodes have shown emission at the radio main pulse and interpulse positions[56–60] and a few at other phases also[61,62]. The duration of the pulse has not been constant. Gupta *et al.*[57] observed two peaks (Figure 4,*f*) with a probability of 1.4×10^{-4} in the phasogram in the data collected at Ootacamund during 9 runs in February 1977 (but not in the runs in March), which they attribute to the main and interpulses on the basis of their separation; they did not have information on the absolute phase. The estimated flux was $(1.19 \pm 0.33) \times 10^{-11}$ photons cm^{-2} s^{-1} at $E > 0.5$ TeV. They subsequently[63] revised their energy and flux estimates to 6.4 TeV and $(8 \pm 2) \times 10^{-12}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ due to the recalibration of the light collection efficiency of the mirrors.

More recent observations have shown transient emission of several minutes duration, essentially because special efforts were made to search for them only since the early eighties. The burst of 15-m duration observed by the Durham group[64] in October 1981 showed a broad pulse of width of about 0.3 in phase (Figure 4,*a*). Absolute phase was, however, not available. The estimated flux was $(2 \pm 0.3) \times 10^{-10}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at $E > 3$ TeV during the burst. The burst reported by the Tata group[59] was also of 15-m duration and has shown a narrow pulse at the position of the radio main pulse (Figure 4,*b*). They reported a flux of $(2.5 \pm 0.6) \times 10^{-10}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at $E > 1.2$ TeV during the burst. An important feature of this observation is that two telescopes tracked the Crab from locations separated by 11 km and both of them showed the signal while a third telescope adjacent to one of them but looking 8° away did not show any signal. This confirms that the signal is from the Crab and not due to any terrestrial phenomenon like lightning. Recently, another burst of similar duration and flux in the main pulse have been seen by the Tata group[65] from their Pachmarhi Observatory on 2 January 1989.

A very interesting feature has been reported by Vishwanath[60] from an analysis of the data base of the Tata group on the Crab in the TeV energy range. He divided all the data collected during the period 1979–85 into mini runs of one-minute duration each and selected those which showed large χ^2 for the phase distribution. Since χ^2 is only a measure of deviation from uniform distribution, excess events in individual mini runs can be at any phase and the resultant phasogram for the high χ^2 runs should show a uniform distribution if the parent distribution is uniform. However, he found that the distribution showed not only peaks at the main and interpulses but also some small excess in between the two pulses compared to the rest of the phase region (Figure 4,*c*). Based on these observations, he obtained a mini burst flux of $(1.6 \pm 0.3) \times 10^{-10}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at $E > 0.6$ TeV during

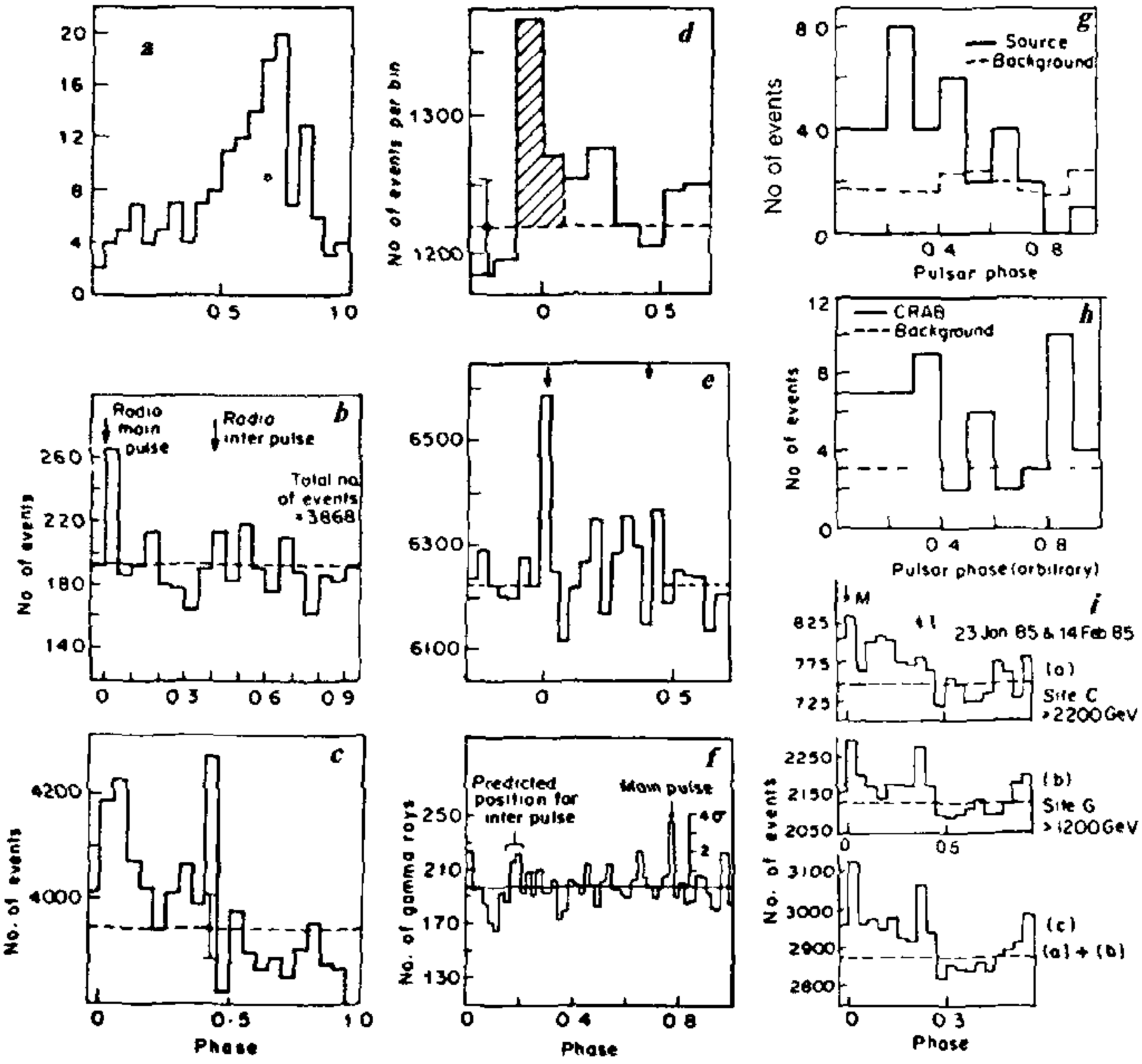

Figure 4. Light curves obtained from the Crab pulsar in various observations. They vary from narrow single, occasionally double, pulse to a broad pulse covering half the period with emission in between the main and interpulses. *a*, Gibson *et al.*[64]; *b*, Turner *et al.*[58]; *c* & *i*, Vishwanath[60]; *d*, Bhat *et al.*[59]; *e*, Dowthwaite *et al.*[66]; *f*, Gupta *et al*[57]; *g*, Acharya *et al.*[78]; *h*, Acharya *et al.*[79].

1982–83 and $(2.1 \pm 1.1) \times 10^{-11}$ photons cm^{-2} s^{-1} at $E > 2.2$ TeV during 1984–85. Furthermore, data on two particular nights in 1985 showed a similar phase distribution (Figure 4,*i*) in the two telescopes, separated by 11 km.

The only instance of pulsed emission lasting for a long period of time was reported by the Durham group[66] during 103 h of observation from September 1982 to November 1983. The emission was confined to a narrow phase region at the radio main pulse with some weak evidence at the interpulse (Figure 4, *e*). Additional support for the genuineness of the signal was that the excess events came preferentially from the centre of the field of view identified from the relative arrival time information from well-separated detectors. They quote a probability of 6×10^{-7} for the observation to be due to chance. The detected signal constitutes $(0.233 \pm 0.054\%)$ of the cosmic-ray flux, the weakest among all reported. The resulting flux is $(7.9 \pm 1.8) \times 10^{-12}$ photons cm^{-2} s^{-1} at $E > 1$ TeV. There was, however, no evidence for transient emission during this period. The University of California collaboration[58] also found emission at the main pulse in 22 h of observation during the two overlapping months of September and October, 1982. Their pulse width (Figure 4,*d*), however, is broader than that in the Durham observations. They found evidence that the signal enhances from 2 σ to 3.2 σ when they select showers with a broader lateral distribution of Cerenkov light. A broader lateral distribution is expected[67,68] for gamma-ray showers compared to cosmic-ray proton-induced showers. The flux reported is $(2.5 \pm 0.8) \times 10^{-11}$ photons cm^{-2} s^{-1} at $E > 0.2$ TeV.

Recently, the Whipple collaboration[69] also reported one episode of 29-min duration at UT 04.02 on 11 January 1991 during which pulsed emission is seen at the position of the main pulse with an overall chance probability of $< 1\%$. This result was obtained with a more sophisticated selection of gamma-ray-like events, called 'supercuts', recently developed by them[70], and therefore suggests that the TeV radiation from the pulsar probably consists of gamma rays.

The light curves obtained in these various observations are shown in Figure 4. We shall discuss these results along with those in PeV energy region later.

To summarize, pulsed emission in the TeV region is mostly transient in nature though on one occasion some weak emission over a long period has been detected. The light curve seems to be highly variable, often only the main pulse is seen, occasionally both the pulses are seen and at other times a broad pulse encompassing the main and interpulses. The fluxes reported are in the region of a few times 10^{-11} photons cm^{-2} s^{-1}.

In the PeV region for a long time there were no reports of pulsed emission, not even upper limits, the main reason being that the clocks operating with the EAS arrays were not accurate enough to do pulsar analysis. Only recently this lacuna has been rectified in the EAS arrays. The arrays have been modified to provide good angular resolution and also equipped with large area muon detectors. The only report of pulsed emission lasting for a long period has come from the Ooty group[38]. Their phasogram, for the three year period June 1984 to May 1987, shows a 3.9 σ excess at the interpulse position. They estimate an overall chance probability of 1.6×10^{-3} of observing such an excess at any position in the phasogram. The reported flux is $(4.1 \pm 1.2) \times 10^{-13}$ photons cm^{-2} s^{-1} at $E > 0.2$ PeV. They claim that the signal enhances somewhat if they select older showers (shower age > 1.4). Monte Carlo simulations by several groups[71-73], however, do not show any detectable difference in the age parameter between gamma ray and proton showers. There are no other reports of positive detection during the period 1984–87. The Los Alamos group[74] does not see any significant excess at any phase in their data collected during April 1986 to August 1989, which overlaps part of the period of the Ooty observations. They set a 90% confidence level upper limit of 6.9×10^{-14} photons cm^{-2} s^{-1} at $E > 50$ TeV, which corresponds to an upper limit of 2.1×10^{-14} at $E > 200$ TeV, factor of 20 smaller than the Ooty flux. The reasons for these discrepancies are not clear.

An important development of far reaching consequence to PeV gamma-ray astronomy has recently taken place. The Baksan group[75] reported a PeV energy burst from the direction of the Crab nebula during the period 14.00–19.00 UT on 23 February 1989 with their EAS array at Baksan (atmospheric depth, 840 g cm^{-2}; long. 43° E; lat. 43° N). They recorded 57 events of energy ≥ 0.2 PeV within 2°.5 of the Crab direction, corresponding to an excess of 3.9 σ (according to the likelihood ratio method of Li and Ma[76]) over the expected background of 31.1 events. The source transited at 16.5 UT. Since they searched for 333 days during 1985 and 1989 the overall chance probability for such an excess to occur was 0.02. Even though a reanalysis[77] of their data resulted in a reduced significance in the same angular bin, it is important to note that the excess still remains at a 3.1 σ (Li and Ma) significance level. This observation triggered the Tata group[78,79] to examine their data for that day only i.e. 23 February, from the EAS array operating at Kolar Gold Fields (KGF; atm. depth 920 g cm^{-2}; long. 78.3° E; lat. 12.9° N). They detected the burst during the time interval 13.25–16.0 UT. The Crab transit at KGF was 14.1 UT. KGF recorded 35 events of energy ≥ 0.1 PeV against an expected background of 17.8, within an acceptance angle of 4° radius, corresponding to an excess of 3.4 σ (Li and Ma). This is the first time that what may be regarded as a simultaneous observation of PeV gamma rays has been reported from any source.

The event times were recorded in the KGF experiment with an absolute timing accuracy of ~ 1 ms. They could therefore analyse the data for pulsed emission and found that the first half of the period, which spans both the main and interpulses seen at radio frequencies, contained 26 events against an expectation of 8.9 (Figure 4, *g*). Thus all the excess events in the DC mode seem to be concentrated in the first half of the pulsar period. The significance of this result is 0.01. An analysis, by the Tata group[79], of the arrival times of the Baksan events (supplied by the Baksan group) also showed excess events in one half of the phase (Figure 4,*h*) though absolute phases were not available in this case. The significance of this result is 0.05 if the main pulse position is identified to be at phase 0.8 in this phasogram. This is the first time that pulsed emission of PeV gamma rays has been detected from Crab.

This Crab burst on 23 February 1989 has subsequently been confirmed by two more groups. The Gran Sasso collaboration[80,81], using the EASTOP array (long. 13.6° E, lat. 42.5° N), where the source transit was at 18.4 UT, detected 38 events above 0.2 PeV within an acceptance angle of 1.6° radius against an expected background of 25.5 at a significant level of 2.1 σ (Li and Ma). There is some indication that the ON source events are somewhat older than normal cosmic-ray showers. They also find an asymmetric light curve with 9 out of 13 older showers contained in one half of the period. Absolute phases were not available in this case also. An independent lower energy trigger in their experiment also showed an excess of 1.2 σ (Li and Ma).

The variation of the Crab zenith angle and the 15-min-counting rates from the three experiments are shown as function of UT in Figure 5. It is seen that the burst has lasted several hours starting at 13:15 UT or earlier and ending at 19.00 UT.

Recently Chudakov[77] has reported the results of the Tien Shan array which also show an excess of 2.4 σ (Li and Ma) from the Crab during its meridian transit at Tien Shan, which is only 3 east of KGF in longitude. The Ooty EAS experiment is in a location to detect the

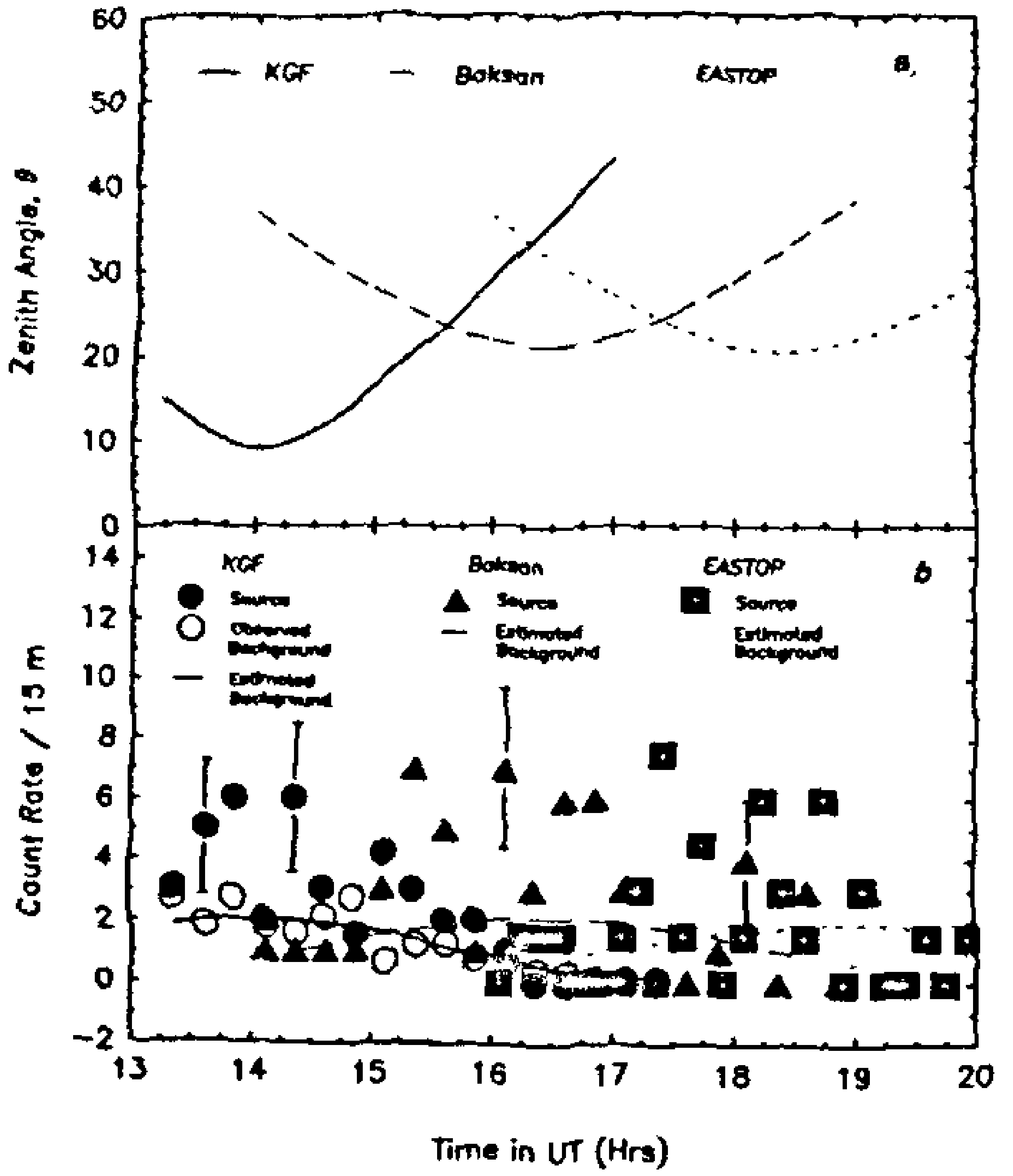

Figure 5. a, Variation of the zenith angle of Crab with time on 23 February 1989 for the KGF, Baksan and EASTOP arrays. b, Counting rate in 15-min intervals of events arriving from the Crab direction, plotted against Universal Time for the KGF, Baksan and EASTOP data. The background rates of cosmic rays are estimated assuming an angular distribution of $\cos^7\theta$ and normalized to the total expected background over the respective periods. The open circles represent the background at KGF obtained from the data itself.

burst and was in operation, but there is no report from that group as yet. Thus at least four different experiments have recorded the burst in the proper time sequence, confirming the reality of the burst. The probability that all the four groups have recorded the respective excesses from the same source on the same day purely due to chance is 6×10^{-6}. If we further consider that the KGF group has recorded a non-uniform phase distribution also, then the overall probability is 1.3×10^{-7}. Even if we take into account the reduced significance of the Baksan result and also the fact that they have extended their observations from 333 to 1256 days, this overall probability works out to be 3.5×10^{-6}.

Weekes[82] opines that the reduced excess in the Baksan result made the combined effect only marginally statistically significant and concludes that there is no strong evidence yet for emission from the Crab. The quantitative estimate of the combined probability, given above, does not corroborate his opinion and therefore his conclusion. The burst remains statistically very significant in spite of the reanalysis of the Baksan data because (i) the excess in the Baksan data on 23 February remains by itself, even after reanalysis, at a significance level of 3.1 σ; (ii) four different experiments operating at widely separated locations on the globe have recorded excess events on that day from Crab in the expected time sequence, and; (iii) the combined probability that all the four experiments have seen the excess on that day from Crab purely due to background fluctuations is 3.5×10^{-6}.

The Akeno group[83] has not seen any excess during 10–12 UT and the HEGRA group[11] also did not record any excess with their Canary Islands array, where the Crab transit time is 20.6 UT. These reports help to define roughly the starting and stopping times of the burst as indicated earlier. The temporal structure of the burst reconstructed by the Tata group[79] using the observations of the KGF, Baksan and EASTOP groups, is shown in Figure 6.

If the radiation responsible for the showers from Crab during the burst are gamma rays, then the muon content of these showers must be small compared to the normal cosmic-ray showers as discussed earlier. It is estimated from Monte Carlo simulations that gamma-ray showers should contain less than 10% of the muons in proton-initiated showers. Of the four experiments cited above, only the KGF array had muon detectors of total area of about 200 m^2 and could measure the muon content. The KGF experiment showed that showers from the direction of Crab contained nearly the same number of muons as in normal cosmic-ray background showers. The ratio of the muon content in the excess showers from the Crab to that in background showers was estimated to be 0.93 ± 0.34. Based on this, it could be stated that at the 95% confidence level the muon content in the excess showers from the Crab was greater than 37% of that in normal cosmic-ray showers. It is of importance to note here that the Kiel group[84], who first discovered Cygnus X-3 as a PeV gamma ray source, also found that the muon

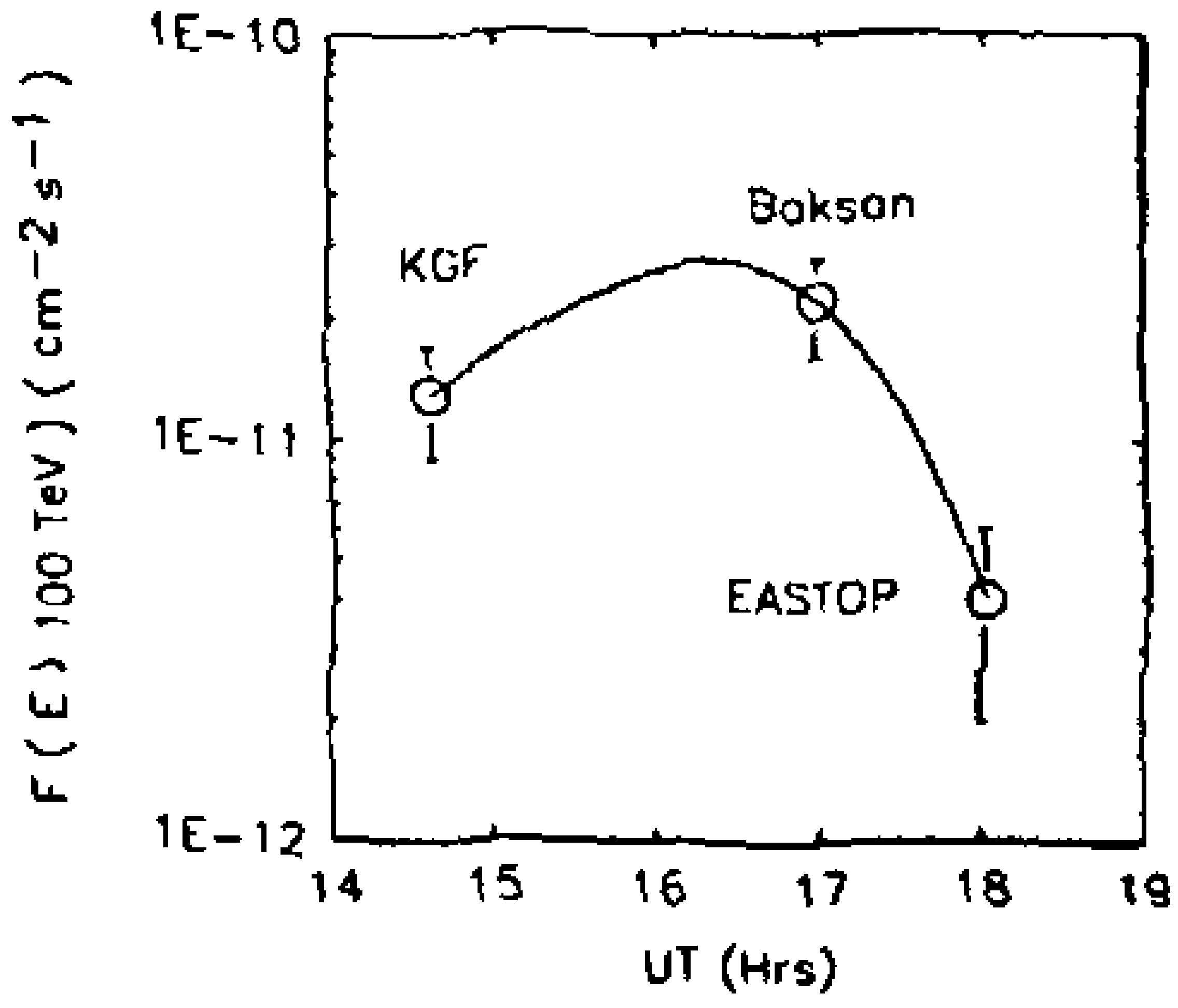

Figure 6. Variation of the excess events of energy > 100 TeV from Crab with UT during the burst on 23 February 1989 from the KGF, Baksan and EASTOP experiments.

content of showers from that object also was large. The Los Alamos group[85] also report a similar finding for showers in the burst they detected from the X-ray binary source Hercules X-1. These observations regarding the muon content of the showers raise several important questions. Are gamma-ray interactions different at PeV energies compared to lower energies as suggested by some authors[86–88]? Are the primaries of these showers neutrinos which interact with almost hadronic cross-section as expected in some composite models[89]? Or is Crab emitting a hitherto unknown type of strongly interacting stable neutral particle? If the third alternative is the case then the mass of the neutral particle should be less than 40 MeV c^{-2} in order to maintain phase locking over half the Crab pulsar period. Such a low mass particle should have been detected in the accelerator experiments.

Let us now examine the features of the light curves obtained in the TeV and PeV observations of Crab shown in Figure 4. It is interesting to note that episodes lasting several hours (Figure 4, *d–i*) show in general a broad peak encompassing both the main and interpulses. While the 15-min burst reported by Gibson *et al.*[64] (Figure 4,*a*) shows a broad peak, the burst of same duration seen by Bhat *et al.*[59] (Figure 4,*b*) has a narrow main pulse. The recent burst seen on 2 January 1989 by the Pachmarhi group[65] also shows a narrow main pulse. The mini bursts reported by Vishwanath suggest, apart from the two pulses, emission in between also (Figure 4,*c*). There are also occasions when narrow main pulse or interpulse or both are seen (Figure 4, *e&f*). Thus there is ample evidence for variability of the light curve apart from the emission itself. Manchester and Taylor[90] noted a long time back that the emission in between the pulses increases with energy of the photons. This trend seems to continue to TeV and PeV energies, though quantitative estimates are not yet available. Variability of the light curve is seen at lower energies also. For example, the COS B observations[91] show that the intensity of the main and interpulses changes with time. In fact, the ratio of the intensity in the interpulse to that in the main pulse decreased with time during 1973–80. Dowthwaite *et al.*[66] also found that the ratio in the TeV energy range during 1982–83 is small and consistent with the nearest COS B observations. Ozel[92] suggested that this variation in the ratio is due to the free precession, and possibly nutation, of the pulsar with a period of 10.75 years. His fit of a sinusoidal curve to the COS B and SAS-2 dats is shown in Figure 7 along with the result of Dowthwaite *et al.* If this is the case, then combining observations over a long period of time is not a good procedure since it will not reveal the variations and also the signal will be diluted as more background is allowed in when one pulse or the other is weak. Obviously, measurement of the features of the light curve in the TeV and PeV regions with high sensitivity detectors is of utmost importance.

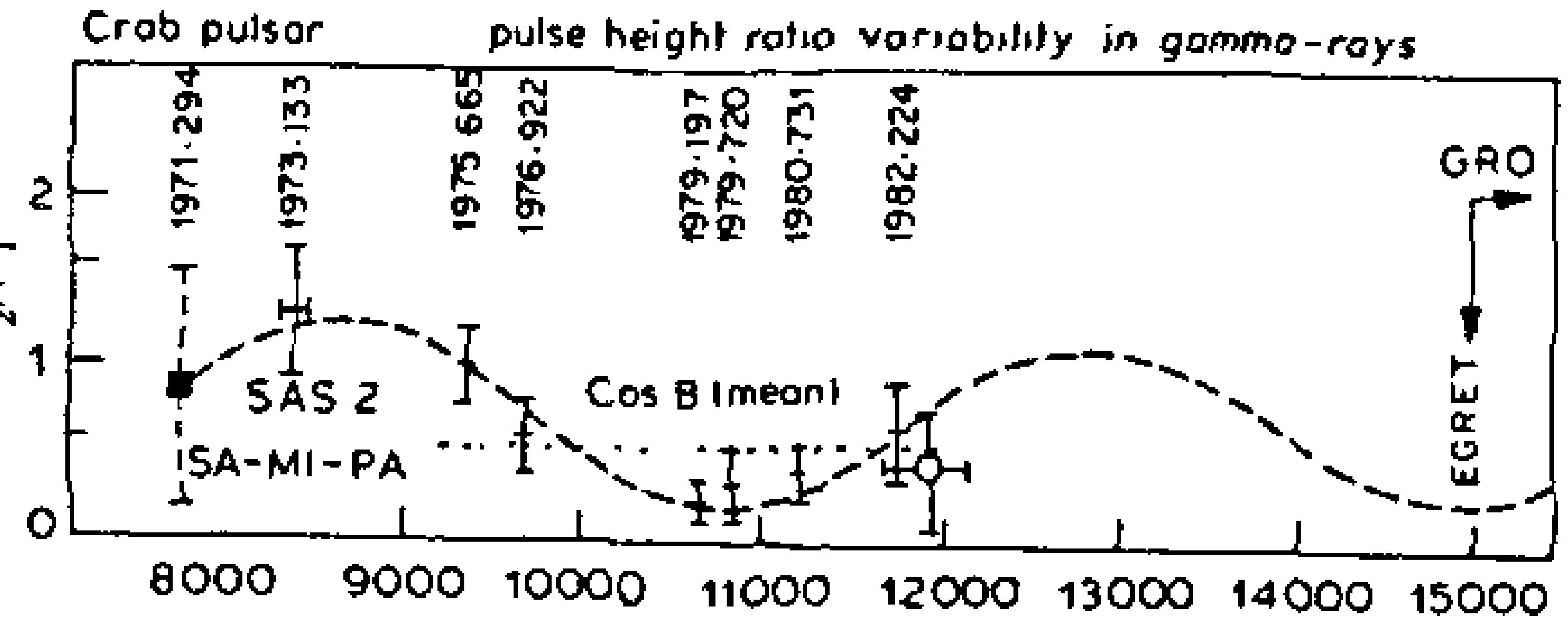

Figure 7. Dependence on time of the ratio of the intensities in the interpulse and the main pulse of COS B observations in the GeV energy region fitted to a sinusoidal curve by Ozel[92]. The observation of Dowthwaite *et al.*[66] in the TeV energy, shown as open circle, also agrees with the hypothesis that this variation is due to the precession of the neutron star with a period of 10.75 years.

It is clear that steady pulsed emission from Crab, if at all present, is very weak and perhaps just at the threshold of sensitivity of the present day detectors. The pulsed emission can be detected only when it is enhanced for short durations or when the background fluctuates on the lower side as in the case of the mini bursts reported by Vishwanath. In his analysis, 263 out of a total of 10,489 mini runs show the signal; so the time averaged flux over the entire period of observation works out to be $(4.0 \pm 0.8) \times 10^{-12}$ photons $cm^{-2}\,s^{-1}$ at $E > 0.6$ TeV, which is compatible with the time averaged flux of $(7.9 \pm 1.8) \times 10^{-12}$ photons $cm^{-2}\,s^{-1}$ at $E > 1$ TeV reported for the period 1982–83 by Dowthwaite *et al.*[66], considering the uncertainties in the estimates of energies and fluxes. Though Dowthwaite *et al.* mention that there is no evidence in the data for sporadic activity on time scale of minutes as strong as that reported by Gibson *et al.*[64], it is not clear whether the detected emission is due to a number of mini bursts spread over the entire observation time as in the case of the Ooty observations. It is, therefore, very important to search for such mini burst activity.

Some gamma-ray astronomers are somewhat skeptical about the episodic activity in the TeV and PeV region arguing that the episodes are not reproducible and several of them are at marginal significance. In the case of Crab pulsar, however, there are several features that suggest that at least some of the observations are not due to background fluctuations. These are:

(i) The Smithsonian group[48,62] found the signal only when they selected gamma-ray-like events
(ii) The Tata group[59,60] observed the episodes on at least two occasions at two different locations 11 km apart; they did not see any excess in the telescope looking away from Crab
(iii) The Durham group's[66] observation shows that the signal is concentrated near the direction of the source
(iv) The University of California collaboration[58] found

the signal during the part of the Durham group's observation

(v) The same group found that the signal is enhanced when *gamma-ray-like* events are selected

(vi) Bursts of similar duration (15 min) and intensity were observed by the Durham[64] and the Tata[59,65] groups

(vii) The PeV energy burst on 23 February 1989 was seen by four different groups at widely different locations on the globe.

Thus TeV and PeV emission from the pulsar appears to be sporadic in nature and future efforts should be concentrated on detecting these with coordinated observations by several groups.

The fluxes and upper limits reported in the various observations are listed in Table 2 and shown in Figure 8 and compared with theoretical models.

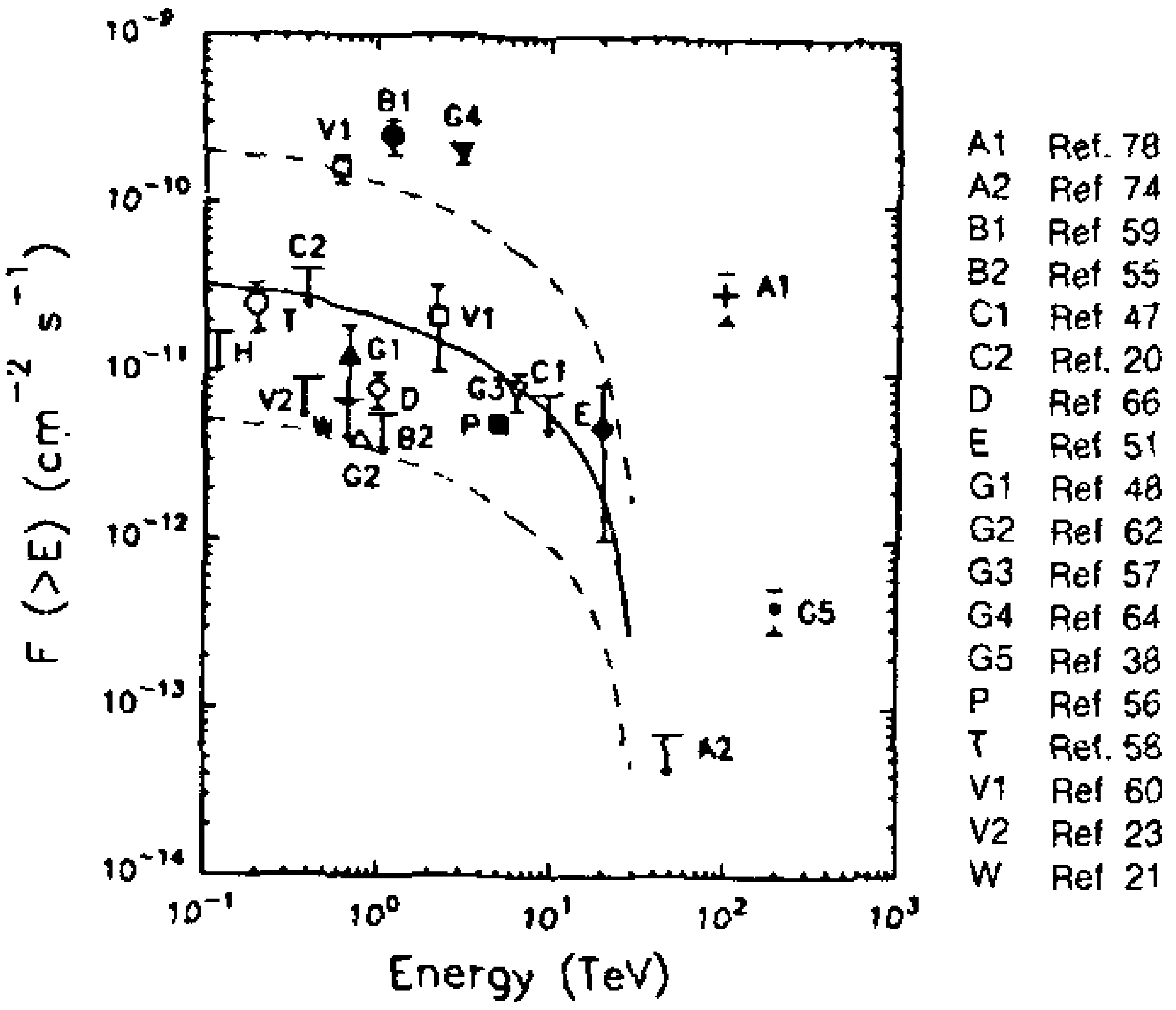

Figure 8. Energy spectrum of gamma rays from the Crab pulsar. *The solid curve is the prediction of the model of Bogovalov and* Kotov[94]. The dashed curves are the result of fluctuations in the product $T\lambda$ by a factor of 2.5 on either side, estimated by us. The points marked B1, G4 and V1, which are due to transients, are *interpreted as due to temporal variations in this parameter.*

Theoretical models for TeV and PeV gamma-ray emission from pulsars are not yet well developed, perhaps because the observations are not yet on a firm statistical footing. In the lower energy region, however, some models have been put forward to explain the light curve as well as the energy spectrum. Cheng *et al.*[41] proposed a model in which electrons and positrons are accelerated in the outer gap in the magnetosphere of an *obliquely rotating pulsar, where large electric fields* can be sustained. These particles generate photons due to various electromagnetic processes, which in turn create $e^{\pm}$ pairs. The pulsed low-energy gamma rays are a result of synchrotron radiation from these $e^{\pm}$ pairs. Up to a few GeV the predictions of the model on light curve and spectra agree with observations on Crab as well as Vela pulsars. A small fraction of the $e^{\pm}$ is lost by inverse Compton scattering on the soft photons, which are boosted to a few TeV. In Crab, these photons are absorbed by the soft photons and create $e^{\pm}$, which synchrotron radiate with a characteristic energy of ~ TeV. However, the authors argue that these gamma

Table 2. TeV and PeV observations from Crab pulsar

Ref	Epoch	Threshold energy (TeV)	Significance (σ s)	Flux (photons cm^{-2} s^{-1})	Remarks
Positive detections					
48	1971	0.68		$(1.3\pm0.6)\times10^{-11}$	
56	1972–73	5.0		5×10^{-12}	
62	1973	0.8	5.1	4×10^{-12}	
51	1975	20.0		$(4.7^{+5.5}_{-3.7})\times10^{-12}$	
57	Feb, 1977	0.5	3.6	$(1.2\pm0.3)\times10^{-11}$	
64	23 Oct 1981	3.0		$(2\pm0.3)\times10^{-10}$	
66	1982–83	1.0		$(7.9\pm1.8)\times10^{-12}$	
58	Sep–Oct. 1982	0.2	3.2	$(2.5\pm0.8)\times10^{-11}$	
60	1982–83	0.6		$(1.6\pm0.3)\times10^{-10}$	
	1984–85	2.2		$(2.1\pm1.1)\times10^{-11}$	
19	23 Jan. 1985	1.2	5.1	$(2.5\pm0.6)\times10^{-10}$	
38	1984–87	200.0	3.9	$(4.1\pm1.2)\times10^{-13}$	
75	23 Feb. 1989	200.0	3.9	$(1.1\pm0.3)\times10^{-11}$	
78	23 Feb. 1989	100.0	3.9	$(1.3\pm0.4)\times10^{-11}$	
80	23 Feb. 1989	200.0	2.1	$(2\pm1)\times10^{-12}$	
Upper limits					
47	1969–70	10.0		7.5×10^{-13}	
20	1983–84	0.4		1.1×10^{-11}	
21	1986–88	0.7		6.8×10^{-12}	
74	1986–89	50.0		6.9×10^{-14}	
55	1988–89	1.1		5.6×10^{-12}	
23	1988–89	0.4		7×10^{-12}	

rays may not be able to escape further absorption in the magnetosphere itself, except when density fluctuations occur in the secondary flows. They predict only a single pulse in the light curve because the inward-moving TeV gamma rays pass through strong magnetic fields and are absorbed by pair creation. The observations, however, show that both pulses as well as a broad pulse are seen often. Also, there is no prediction of the energy spectrum in the TeV region.

Bogovalov[93] suggested that in an aligned rotator, a rotational discontinuity could be formed in the flow of the plasma near the light cylinder, and particles are accelerated in this discontinuous region to TeV energies, deriving energy from the azimuthal magnetic field generated by the rotating neutron star. These particles then produce the TeV gamma rays by the inverse Compton scattering on the thermal photons emitted by the neutron star. The gamma rays can easily escape and be detected as they are produced near the light cylinder. Bogovalov and Kotov[94] calculated the energy spectrum of the gamma rays in this model. Their spectrum is shown in Figure 8. In their model, the flux is proportional to $T^2\lambda^2$, where T and λ are the surface temperature of the neutron star in K and the plasma density in units of the Goldreich density respectively. Their result for $T = 10^6$ K and $\lambda = 10^3$ is shown as the full curve in the figure. The dashed lines are drawn by us for a factor of 2.5 variation in $T\lambda$, commensurate with the upper limit of 2.5×10^6 K for the surface temperature derived by Harnden and Seward[95]. It is seen that almost all the observations agree with this model, except the burst events in the TeV region marked B1, G4 and V1 of references 59, 64, and 60 respectively. These are suggested to be due to sudden increases in the surface temperature, perhaps, during starquakes. The two points from Vishwanath[60] marked V1 at 0.6 TeV and 2.2 TeV correspond to different periods of time separated by two years. The widely different intensities may be due to different values of $T\lambda$. Bogovalov and Kotov, however, have not calculated the light curve. The long term flux of the Ooty group[38] and the seven-hour burst seen by the KGF and other groups[77–81] are not reproduced in this model since there is sharp cut off at a few tens of TeV. To explain these, one may have to consider acceleration of protons to PeV energies and subsequent photo–nuclear interactions with the ambient photons and production of π^0s, which, then decay into gamma rays. Cheng *et al.*[41] consider briefly such a possibility within the light cylinder, but conclude that the gamma rays cannot escape creation of Sturrock pairs in the local magnetic field. The proton acceleration process may, however, just be possible in the Bogovalov–Kotov model.

Summary

The Azwidth method employed by the Whipple group seems to establish that the Crab nebula is a steady emitter of TeV energy gamma rays and can be considered as a 'standard candle' in this energy region. The Compton-synchrotron model agrees well with the observations in the TeV energy region with an ambient nebular magnetic field of 3×10^{-4} G, though it seems to fail at lower energies. The 'hadronic' model of Cheng *et al.* does not predict the spectrum correctly, though the fluxes agree in certain energy regions. Both processes may be operative and further observations over a wider energy range with more accurate estimates of energies and fluxes are needed to establish the energy spectrum on a firm basis. The PeV observations are difficult to understand in any of these models. If the appropriate hadron interaction model is incorporated in Cheng *et al.*'s model, better agreement can perhaps be obtained. The muon content in the PeV energy region, however, remains an enigma.

The light curves in the TeV as well as the PeV region seem to be variable with either the main or the interpulse or both being seen as narrow pulses some times, while a broad pulse encompassing both is seen at other times. The fluxes are in general agreement with the model of Bogovalov and Kotov. The transients may be interpreted as due to temporal increase in the surface temperature due to starquakes. To explain PeV observations, further modification of this model is required. The PeV energy burst from Crab, lasting for about seven hours, seen by four different groups is of high statistical significance. The muon content registered by the KGF group in this event as well as in some of the burst events from Cyg X-3 and Her X-1 reported by other groups pose new questions regarding the nature of the particles responsible for such bursts and their interaction characteristics at high energies. A worldwide cooperative effort leading to simultaneous and sequential observation of rare burst events and their detailed characteristics is of utmost importance in this field of TeV–PeV astronomy which, in addition to astronomical aspects of significance, holds the promise of solving the problem of cosmic-ray generation and also of revealing newer aspects of particle physics at super high energies.

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