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Search for a TeV photon signal from the Crab pulsar

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Abstract. Observations carried out in 1988-89 at Gulmarg with the help of a conventional (non-imaging) atmospheric Cerenkov telescope do not indicate the presence of the 33ms-pulsed signal which is characteristic of the Crab pulsar in several spectral bands, including high-energy γ-rays. The resulting upper limit, though not as constraining as the one resulting from the second-generation Whipple imaging Cerenkov telescope, assumes importance in view of the recently recognised limitation of the imaging technique in efficiently retrieving flatter-spectra γ-ray signals on the one hand and the persistent claims about the detection of the Crab pulsar signal by the Pachmarhi group, based on some non-imaging data-cuts, on the other hand.

Key words : pulsars — gamma rays: Crab pulsar; pulsed emission

1. Introduction

The Crab pulsar (PSR 0531 + 21) is one of the 5 galactic radio-pulsars which stand firmly established today as high energy γ-ray sources (hundreds of MeV). In the case of the Crab pulsar, this identification is based on the observation of a bimodal light curve which is characteristic of the source at radio, optical and X-ray wavelengths. The pulsar was first studied in detail in the high energy γ-ray region by the SAS-2 and COS-B satellite experiments and, more recently, by the COMPTEL and EGRET experiments on-board the Compton Gamma-Ray Observatory (Schonfelder *et al.* 1993; Nolan *et al.* 1993). At very high energies, ($>10^{11}$ eV), the successful application of the Cerenkov Imaging Technique (Hillas 1985) has enabled the Whipple group to detect a steady or d.c. signal (cumulative significance $\sim 40\sigma$) from the Crab direction with a flux of $(7.0 \pm 0.4) \times 10^{-11}$ photons cm^{-2}s^{-1} at photon energies $E_\gamma > 0.4$ TeV (Vacanti *et al.* 1991). This signal has been attributed to the plerion, Crab Nebula, rather than the pulsar PSR 0531 +21 lying within it, and has since been confirmed by several other independent groups (Akerlof *et al.* 1990; Tumer et al. 1990; Baillon *et al.* 1993; Goret *et al.*

1993; Krennerich *et al.* 1993), using both imaging and non-imaging data-cuts to reject the cosmic-ray-generated background events. Based on this convincing evidence, it can be unhesitatingly claimed now that TeV γ-ray astronomy has received its long-awaited first standard γ-ray candle in the form of the Crab Nebula.

The corresponding picture with respect to the Crab pulsar is rather uncertain at present (Weekes 1988, 1992; Rao & Sreekantan 1992). Using generation-I atmospheric Cerenkov telescopes in the eighties, several groups (Gupta *et al.* 1978; Dowthwaite *et al.* 1984; Tumer *et al.* 1985; Resvanis *et al.* 1987) have claimed detection of pulsed TeV gamma-rays from this source, exhibiting, both, persistent-pulsed (duration > ~5 days) and episodic-pulsed (duration ~ minutes) emission modes. Quite intriguingly, however, more recent observations with the higher-sensitivity Whipple Imaging Telescope (Lang *et al.* 1991; Punch *et al.* 1992) and the ASGAT experiment (Goret *et al.* 1993) have failed to detect pulsed emission, resulting in 3σ upper limits of 1.2×10^{-12} cm^{-2} s^{-1} above 0.4 TeV (Whipple) and 4.6×10^{-12} cm^{-2} s^{-1} above 0.6 TeV (ASGAT). On the contrary, the Tata group, using an augmented Cerenkov detector array at Pachmarhi (Vishwanath *et al.* 1994), have reported the detection of a significant TeV photon flux of pulsar origin in their Crab data-base for the period 1979-1985. Unlike the Cerenkov Imaging Technique of the Whipple group, the Pachmarhi group have sought the rejection of a significant fraction of the background cosmic-ray events by applying data-cuts based on the lateral distribution of the Cerenkov photons and the event arrival-direction information. Similarly, the earlier Crab data-bases, some of which have indicated pulsar emission in the persistent-pulsed or episodic-pulsed emission modes, as mentioned above, have all been obtained with generation-I systems where no Whipple-like imaging data-cuts are involved. The implied discrepancy between the results obtained from imaging (Whipple) and non-imaging (Tata / Durham) systems indicates that the sensitivity of the Whipple imaging system may be significantly lower in the case of photons from the Crab pulsar, as compared to that for photons of Nebular origin, possibly due to the well-known dependence of the image parameters (length, azwidth) on the primary energy (Lewis *et al.* 1993). As pointed out recently by Bhat *et al.* 1994) and Aharonian (1994), such a possibility exists, for example, if the photon spectrum of the PSR 0531+21 signal in the VHE region is significantly harder (flatter) than the corresponding nebular spectrum (integral photon spectral index ~ -1.5). This limitation of the imaging parameters, associated with biases in image selection procedures in the analysis of higher energy events from sources with hard spectra, has also been referred to by the Whipple group in a recent communication (Biller *et al.* 1995). In view of this, it is meaningful to continue searching for the Crab pulsar signal with conventional, non-imaging, Cerenkov telescopes also. This provides the basic motivation for the present work.

2. Experimental details

The Gulmarg atmospheric Cerenkov telescope has been described in detail in Koul *et al.* (1989). One bank of the telescope, comprising 3 x 0.9m aperture mirrors, placed on equatorial mounts and provided with a synchronized drive system, was deployed for the present observations. A fast photomultiplier tube (PMT) of 5cm sensitive photocathode diameter (RCA 8575) is placed centrally in the focal plane of each mirror to view the night sky on clear, moonless nights in a field of 4° angular diameter. Three-fold coincidences are generated from the 3 PMT detectors with a resolving time of 20ns, after ensuring that the three telescope elements have an overlapping field of view. The resulting prompt coincidence rate (PCR), mostly due to atmospheric Cerenkov events initiated by cosmic-ray protons (p-ACE) and γ-ray photons (γ-ACE), has, in addition, a non-negligibile contribution (~10% of PCR) from the chance- or delayed- coincidence rate (DCR) of photomultiplier shot-noise origin. The absolute epoch of each PCR and DCR event is logged wth an absolute time accuracy of ± 150 μs (Sapru *et al.* 1990). An LED lamp-based background light compensation circuit is provided to keep the total light incident on each PMT essentially constant in the course of observations each night.

The work reported here is based on observations made in the tracking mode during 1988 November 7- December 7 and 1989 October 24 - November 8 and, in the on-off mode, during 1989 November 21 - December 3. The single's rates of the three detector channels were maintained around (40 ± 5)kHz, leading to an average DCR of ~0.11 Hz, in good agreement with the expected three-fold chance coincidence rate of ~0.08 Hz for a coincidence resolving time of ~20 ns. The mean Genuine Coincidence Rate (GCR ≡ PCR-DCR), averaged over the zenith angle (ψ) range covered on various observation nights (19° to 40°), is found to be ~0.53 Hz. This yields a threshold photon energy of ~4 TeV and an effective Cerenkov light pool radius of ~140 m for the Gulmarg system (Senecha *et al.* 1992).

3. Data analysis and results

The entire data-set, comprising 51.2 h of data in the tracking-mode and 29.8 h of data in the on-off mode of observations, was first examined for its general quality by subjecting it to the following standard test : Using a convenient averaging time-interval of 2 minutes, the GCR was plotted as a function of the telescope zenith angle (ψ) and an empirical function $\mathrm{Cos}^{m}\psi$ was fitted to the data for each individual day separately, using the method of least squares. It is reassuring to note that the range of m values obtained for this fit (m~3.83 ± 0.13) is in accord with the expectation, based on analyses of data from other observation spells for the Gulmarg telescope over the zenith-angle range covered during the present observations. Again, in conformity with the expectation, no perceptible long-term trend is observed when the DCR are plotted against ψ for each day. In the case of on-off scans, the data were subjected to another test for checking their internal consistency, viz., noting the departure 'ΔR' of the counts ratio R (≡DCR -on/DCR-off) from the expected value of unity, where DCR-on and DCR-off are the average DCR values for a given on-source and the corresponding off-source scan respectively. The significance of the parameter ΔR is that an unexpectedly large value for it indicates presence of possible systematic effects which can impair the quality of the GCR data, as, for example, due to the total background light (night sky + LED lamp) incident on the detectors not being adequately matched during the on-and the corresponding off-scans of a given cycle. Adopting a rather conservative approach, we classify as 'clean' those cycles for which $\Delta R \leq 1\sigma$. This, somewhat stringent, criterion was adopted in view of the fact that the frequency distribution of the derived R values was found to be asymmetrical with respect to the expected value of R=1, with a larger frequency of higher R values than could be accounted for in terms of Gaussian statistics. Out of a total of 26 original on-off data-sets, only 13 pass this restriction. The overall GCR counts ratio for these 13 on-off sets turns out to be 0.982 ± 0.015; indicating absence of a d.c. or steady signal from the Crab direction at the sensitivity level of the Gulmarg experiment ($\sim 3 \times 10^{-11}$ photons cm^{-2} s^{-1}).

Next, these on-off spells were subjected, alongwith all the available tracking-mode data, to the standard phasogram analysis to search for the expected 33ms periodic modulation. The absolute epoch of each PCR or DCR event was first corrected for the known time-drift of the system clock (Sapru *et al.* 1990) and then converted to the solar-system barycenter, using the MIT ephemeris (due to D. Richards and I. Shapiro). This time was next converted to the absolute phase of the pulsar PSR 0531+21, using contemporaneous radio-pulsar elements (Table 1), supplied by the Jodrell Bank group (Lyne & Pritchard 1990). The resulting phase values were used to generate 10-bin phasograms for the PCR and DCR events, separately for the two sets of tracking-mode data and the 13 sets of on-source data from the on-off mode. The corresponding GCR phasograms for each data-set were obtained by subtracting the number of events present in a given phase-bin of the DCR phase-plot from the number of events present in the corresponding phase-bin of the PCR plot. The resulting GCR phasograms for the three data sets are shown in Fig.1. As we have used the absolute phase information in deriving these phase plots, we can combine them coherently to get the phase plot for the composite data-set, which is also shown in Fig. 1.

Table 1. Crab pulsar ephemerides used for the phasogram analysis of the three data sets

Observation spell	T (MDT)	ν (s^{-1})	$\dot{\nu}$ (s^{-2})
1988 Nov. 7 – Dec. 7 (Tracking-mode)	2447480.500000	29.9783546206	$-378438.80 \times 10^{-15}$
1988 Oct. 24 – Nov. 8 (Tracking-mode)	2447814.500000335	29.9674391457	$-378261.94 \times 10^{-15}$
1989 Nov. 21 – Dec. 3 (On / Off-mode)	2447845.500000211	29.9664261475	$-378167.74 \times 10^{-15}$

An examination of Fig.1 indicates the absence of a statistically-significant narrow emission feature, expected of the source at $\phi_{33\mathrm{ms}} = 0.0$ (main pulse) or 0.4 (interpulse) from earlier observations in the TeV energy range (Gupta *et al.* 1978; Dowthwaite *et al.* 1984). On the other hand, a broad peak-feature is noted in the phase region $\phi_{33\mathrm{ms}} \sim 0.8$-$0.0$ in the composite phasogram, which, we believe, is not an artifact of any known systematic biases as the same trend is observed when the tracking mode data are divided into sub-sets and the phasogram analysis repeated for each data-set separately. Moreover, the overall morphology of the composite light curve (and the light curves for the two tracking-mode data- sets) in Fig. 1 is reminiscent of the broad light curves reported by the Durham group (Gibson *et al.* 1982) from the Crab pulsar during two 15-minute long episodes. However, inspite of these positive indications, we consider it premature at the present stage to associate the long-term

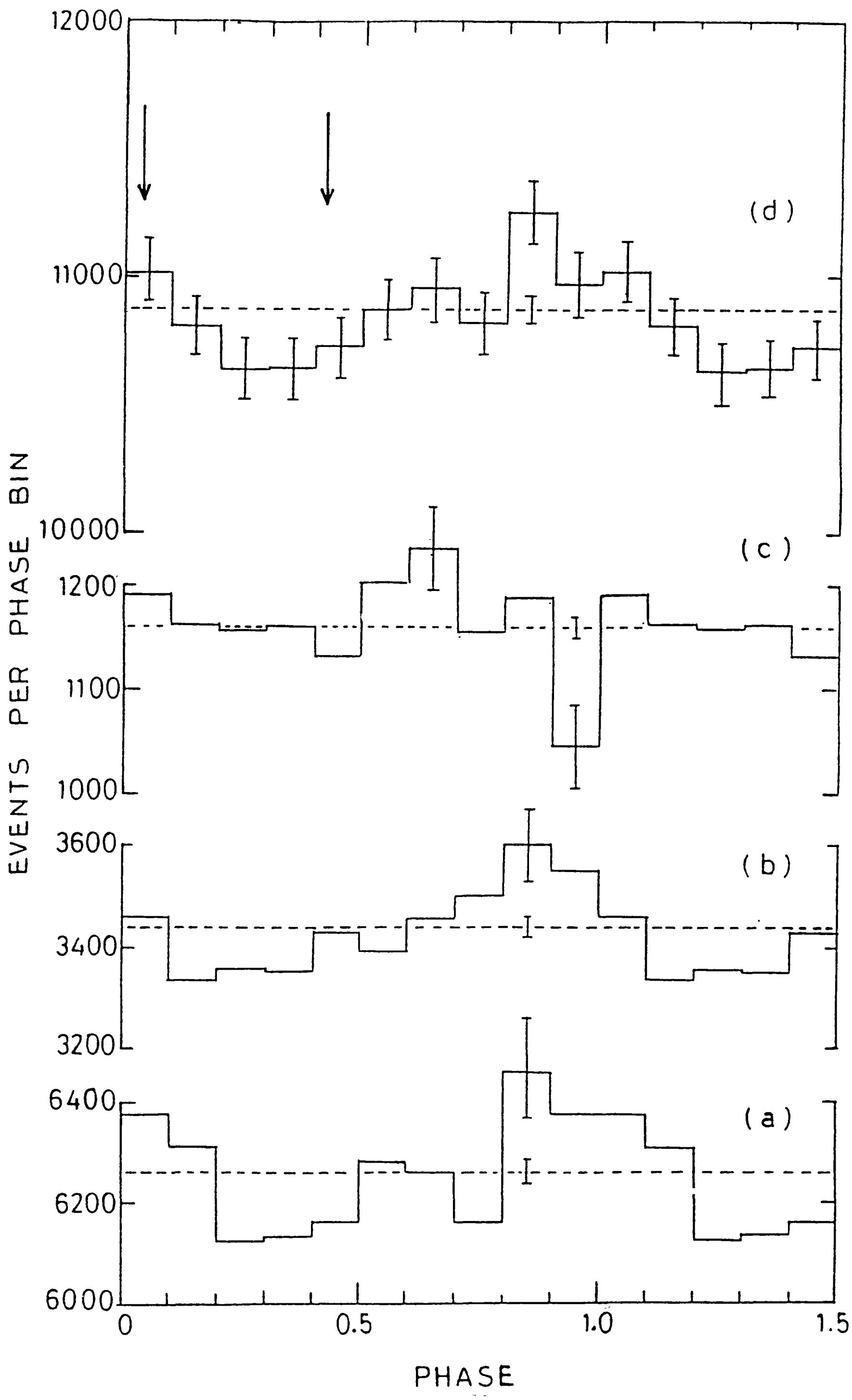

Figure 1. A 10-bin Crab pulsar phasogram obtained by epoch-folding (a) 32.7h of tracking mode data recorded during winter 1988. (b) 18.5h of tracking mode data logged in 1989 and (c) 13 sets of 30-min duration on-scans recorded during 1989. (d) represents the composite phase-histogram for the entire data (a + b + c). Arrows denote the radio main and interpulse positions and the dotted lines, the average rate for each plot. The vertical bars represent ± 1σ Poissonian errors. No emission feature is evident in any phase bin.

trend apparent in Fig.1 (compared with the counts rate in the other bins) with the source, primarily because of its marginal significance and, also, because it is found only in the 2 tracking mode phasograms (panels 'a' and 'b') and not in the on-off mode phasogram (panel 'c'), thereby reducing the overall significance of the peak feature at $\phi_{33\mathrm{ms}}$ ~ 0.8-0.00 from ~3.1σ (panels 'a' and 'b' only) to ~ 2.7σ (Fig.1d). Two other reasons, which favour this cautious approach are, firstly, the unavailability of the absolute phase information for the two Durham episodes which prevents a direct comparison between these light curves and secondly the fact that our results here primarily refer to the persistent-emission mode rather than the episodic emission from the Crab pulsar.

In view of the above mentioned reservations, we, therefore, prefer to claim that the Gulmarg observations on the Crab pulsar during 1988-1989 show no evidence for a pulsed (or d.c) TeV signal on a time-scale of a few days or more. Assuming a ~10% duty-cycle for the pulsed emission, we place a 3σ upper limit of 3.0×10^{-12} cm^{-2} s^{-1} on the time-averaged pulsed flux from the Crab pulsar at E_γ 4 TeV during 1988-89 for an effective collection area of 6.2×10^8 cm^2. This limit is shown in Fig. 2 alongwith some other flux values and limits reported in literature on the pulsed γ-ray signal from the Crab pulsar. Also shown in the figure, mainly for the purpose of illustration, are some representative spectral fits expected from the γ-ray emission model of Bogovalov and Katov (1990). In this model, charged particles, accelerated in the region of a rotational discontinuity in the plasma flow near the Crab pulsar light cylinder, produce TeV γ-rays by undergoing inverse Compton scattering on thermal photons from the neutron star. The resultant TeV photon flux is proportional to $T^2\lambda^2$, where T is the surface temperature of the neutron star and λ is related to the plasma density. As seen from Fig.2, the large scatter in the reported values of pulsed flux and upper limits on the pulsed signal in the TeV energy range, indicates the need for further refinement of the theoretical framework and more observational inputs for providing the requisite constraints to understand the emission mechanisms possibly operating in this system.

4. Conclusions

Our observations with the Gulmarg Atmospheric Cerenkov Telescope, during the 2-year period 1988-1989, yield no evidence for a d.c. or pulsed emission from Crab pulsar at photon energies ≥4 TeV. The status of the Crab pulsar as a source of VHE gamma-rays, therefore, remains under a question mark and more sustained observations are called for in future with higher sensitivity experiments to provide more definitive leads to this important astrophysical problem, including about the possible source association of the broad peak feature seen in Fig.1 at $\phi_{33\mathrm{ms}}$ ~0.8-0.0.

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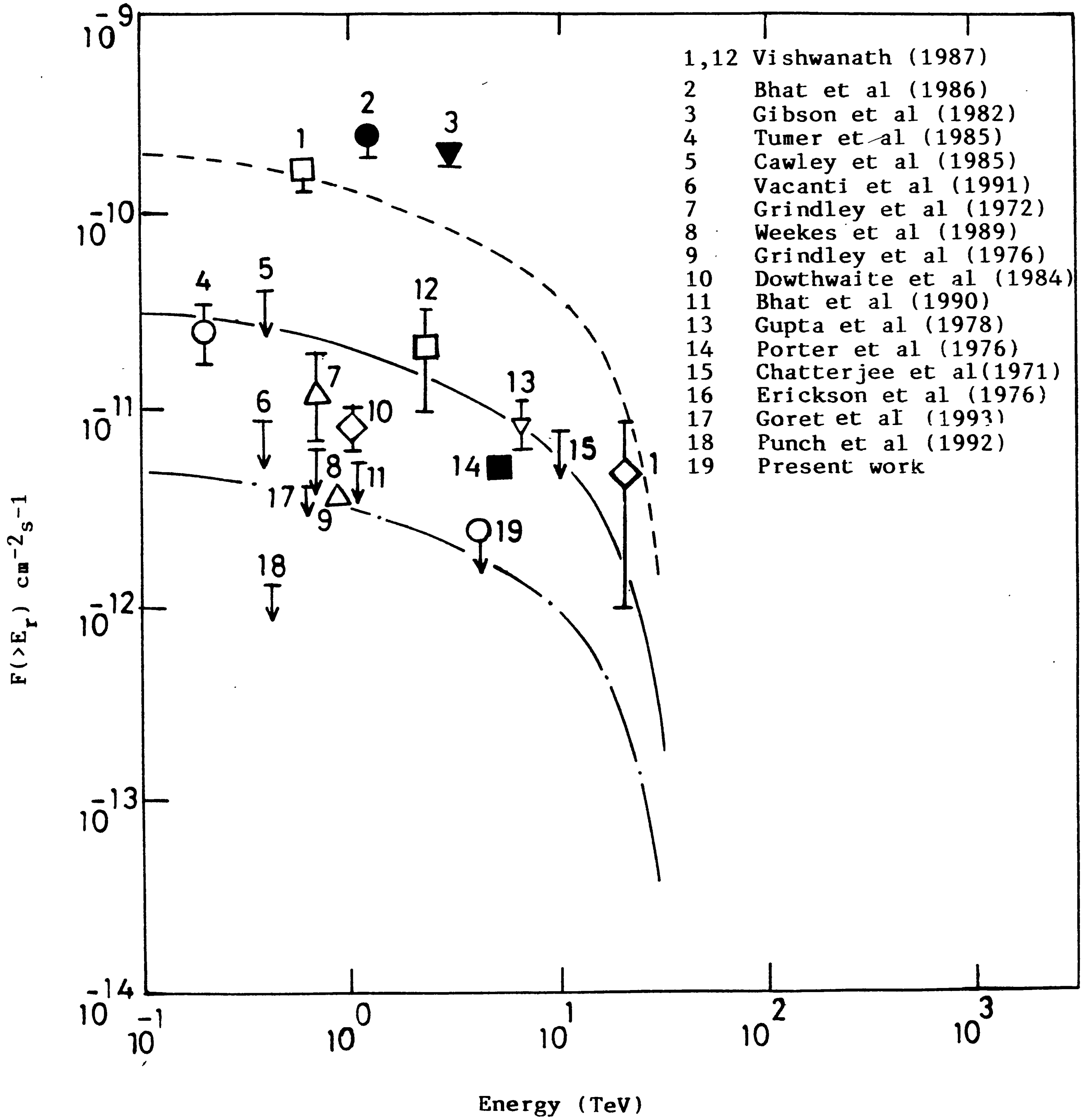

Figure 2. Flux measurements and upper limits reported by various groups for the 33ms pulsed signal from Crab pulsar in the TeV – PeV energy band (from Bhat, 1993). Filled circles (●) represent persistent-pulsed signal and filled squares (■) episodic signal. The full curve represents the spectrum predicted on the basis of Bogovalov and Katov (1990) model for $T\lambda = 10^9$, while the dashed curves represent the spectrum for $T^2\lambda^2 = 4 \times 10^8$ and 2.5×10^8 respectively (from Rao and Sreekantan, 1992).

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