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A Review Of Observational Results On Very High Energy $\gamma-$ ray Emission from Pulsars

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Abstract. Radio pulsars have played a very important part in the growth of VHE (Very High Energy) $\gamma-$ ray astronomy. Apart from their ability to accelerate particles to very high energies, the modest sensitivity of the first generation atmospheric Cerenkov telescopes could be increased with the time signature of the pulsars. The main inference from the telescopes of the '80s was that the time-averaged emission spectra from the lower energies had to steepen in the GeV-TeV energy region. This conclusion has been reinforced in the 90s from experiments with much better sensitivities. However, results from several experiments from the past and the more sensitive experiments at present (for eg, the PACT) can be reconciled by invoking a possibly different component arising in the TeV region. This possible 'Last Hurrah' of the pulsar needs further study from the ground based experiments.

Key words: VHE-$\gamma-$ ray astronomy, Radio Pulsars

1. Introduction

The Crab nebula, the favourite source for origin of high energy cosmic rays in the 60s, was also expected to be a prolific source of VHE gamma rays due to hadronic interactions of cosmic rays in the nebula. The first full scale atmospheric Cerenkov experiment in 1964 of the Russian group set up to find such VHE gamma rays did not find them from Crab or any other source. This was attributed to the possible low sensitivity of the experiments and further progress had to wait for the discovery of pulsars in 1968 which was welcome by both theorists and experimentalists alike. Pulsars with their high magnetic fields could accelerate the particles and thus be the sources of high energy cosmic rays. The experimentalists, on the other hand, could more effectively look for sources since the timing signature of the pulsars would provide higher sensitivity without the need for doing background (control) observations. Most of the studies, which invaribaly gave more atteniton to the Crab pulsar, started as early as 1970 with rather modest mirror areas. The advantage was that when the data were plotted into say a twenty bin phasogram there would be an automatic reduction in the cosmic ray background by a factor of about $\sqrt{20}$ (if it is assumed that the emission is restricted to only one in 20 bins). Almost all the groups working on pulsars in the 70s did find some signals from the Crab pulsar, but the results could not be repeated. Further, some of the detections did not have absolute phase which made comparisons difficult. Several possible reasons for non-reproducibility of the results were proposed : (1) The emission is transient and only if the experiment happened to be on during this transient emission, a signal was seen. (2) The conditions during different observations were not necessarily same: for eg; the atmospheric transparency could be different for different exposures or the energy thresholds from one observation to the next observation could be different. (3) The signal levels were not high (mostly $< 4\sigma$) and thus could be just due to fluctuations leading to the conclusion that there is no VHE gamma ray emission at these energies. Thus while transient emission could not be ruled out, it was becoming clear from experiments in 80s that time averaged pulsar spectra have to steepen at the energies where atmospheric Cerenkov technique starts becoming viable. As we will see below, these earlier tentative conclusions from the VHE experiments have been borne out in general by the exhaustive studies in the 90s on pulsars by the EGRET Experiment on the GRO.The more recent VHE gamma ray experiments, with both imaging and nonimaging techniques, have also not detected any signals below 1 TeV from pulsars like Crab.

While the emission process giving rise to MeV-GeV gamma rays could peter out at sub-TeV energies, it is important to ask whether there is any other process in pulsars which could give raise to GeV-TeV gamma rays. Possibility of such processes had been raised earlier by the outer gap models and this is reinforced by some new versions also. Thus, while the recent trend in the field has been to lower the threshold energies, it is interesting that one has really to look at the higher energy part of the data to detect the emission. After describing new results on several pulsars, results from a new experiment which has started out at Pachmarhi will be specially looked at for evidence for these higher energy emissions.

2. The MeV-GeV region

Pulsar studies have become more interesting for the VHE gamma ray astronomer since the EGRET results. The EGRET experiment detected seven pulsars (see for eg. Thomson,2000). The Crab and Vela had already been detected by the earlier satellites. The important addition to the list was the Geminga Pulsar which had remained a puzzle since 1980. After the discovery of the periodicity in the ROSAT data, the same period was applied to the EGRET data and thus the Geminga pulsar was detected at the MeV-GeV energies. The others are : PSR B1951+32, and the southern pulsars PSR 1706-44, PSR B1055-52 and PSR B1509-58. As for the fluence from these pulsars, Vela is the brightest and PSR B1951+32 is the weakest. An interesting aspect is that these pulsars display a double peak light curve. Only the Crab pulsar has its main and inter peak aligned through out the electromagnetic spectrum. Except for Geminga, where the separation between the Main and the Inter Pulses is 0.5, all other pulsars show separation of 0.4. As for their behaviour at higher energies, all the pulsars except B1509-58 show emission at > 100 MeV. But the light curves change with the dominance of either the main or the inter pulse. Further the spectra show dominant power at energies of < 1 GeV (except for B1951+32) with a falloff at higher energies. All these features indicate a setting in of change in characteristics at higher energies. Irrespective of the fact that the number of events at higher EGRET energies is not large, the possibility of change in pulsar characteristics is quite high. Thus, the VHE gamma ray experiments have the interesting task of finding the cut-off energies for the emission mechanism acting at the MeV-GeV energy region in the environs of the pulsars.

Charged particles accelerated in the pulsar environs radiate giving raise to gamma rays. Different sites for the acceleration of these particles provide the basic difference between theoretical models. Two pulsar emission models for MeV-GeV gamma rays have been very popular in the last decade (for a detailed discussion of these models , for eg see Harding,2000 and the references therein). Polar Cap (PC) models assume that particles are accelerated above the neutron star surface with gamma rays originating from either curvature radiation or inverse Compton induced pair cascade in a strong magnetic field. In Outer gap (OG) models acclearation takes place along null charge surfaces in the outer magnetosphere and gamma rays result from photon-photon pair production-induced cascades.

There are several differences between the two models regarding predictions. In PC models, all pulsars are capable of gamma ray emission but not in OG models where pulsars older than Geminga cannot radiate gamma rays. Thus more gamma ray pulsars are expected to be radio quiet in OG models. PC models predict steep spectral cut-offs due to magnetic pair production attenuation and essentially no detectable emission above about 50 GeV. The more prolific younger pulsars are cut off at lower energies while the weak and older pulsars with low surface fields survive till slightly higher energies. The spectral cut-off predicted in OG models is more gradual. However, they predict an inverse Compton component due to gap accelerated particles with a peak around 1 TeV. While there are variations in the OG models, all models predict a TeV emission component. The atmospheric Cerenkov experiments which start around 50 GeV at present go all the way upto > 10 TeV. If there are other mechanisms starting up at higher energies like the recent versions of the outer gap models predict, the VHE gamma ray experiments should be able to detect them.

3. Results on VHE $\gamma-$ ray emission

(a) The Crab Pulsar

While there have been many observations in the 1970s with and without absolute phase information, we will restrict ourselves to the results in the 80s which in general had absolute phase information. Rao and Sreekantan (Rao and Sreekantan,1990)have given a detailed picture of the nebula and the pulsar at both TeV and PeV energies.

The Durham group, working at the Dugway site in USA, detected a 4.3σ signal at the main pulse phase position from 103 hours of observation at an energy threshold of 1 TeV. This is the only experiment of the 80s which saw a time averaged signal from the Crab pulsar. The flux was found to be $5 \times 10^{-12} sec^{-1} cm^{-2}$. It should be noted that the detected flux is quite small , about 3 per hour!. With arrival direction estimation, they also showed that the signal falls off away from the pulsar direction. The Tata group, earlier at Ooty and later at Pachmarhi, took many hours of observation on the pulsar, detected transients but no time-averaged signal. As a representative of the Tata observations, one can use The Ooty results of 3 years (a total of 105 hours of observation), all with absolute phase, which did not show a signal at the main peak and where an upper limit of $4.6 \times 10^{-12} sec^{-1} cm^{-2}$ for Energy > 800 GeV was derived for the time averaged emission(Vishwanath, 1987) . Recently, a thorough search for pulsed emission has been done with the Whipple imaging telescope(Burdett et al, 1999). Using the data collected between 1995 and 1997, for an exposure of about 73 hours above 250 GeV, they give an upper limit for pulsed emission to be $4.8 \times 10^{-12} sec^{-1} cm^{-2}$ The CELESTE experiment and the STACEE experiments, both with solar arrays, also do not see evidence for pulsed emission in their respective energy regions.

Crab pulsar is the only radio pulsar which has been studied at PeV energies. During 1984-1987, the Ooty group (Gupta et al, 1991) found a 3.9σ signal at the Interpulse position. During the Crab burst seen by KGF, BAKSAN and EASTOP, the events from the direction of the Crab showed a broad peak(Acharya et al, 1990).The CASA array also looked at their data and concluded there is no significant peak at any phase. Fig. 1(c) shows the current status of energy spectrum of Crab Pulsar.

(b)The Geminga Pulsar

Geminga showed up as a very bright object in the Cos-B catalog. It remained a mystery for almost a decade within which a period of 59 sec was used for several VHE $\gamma-$ ray searches. It is only when ROSAT showed that there is a 235 msec pulsar in the direction and EGRET also detected it with the same periodicity that the mystery was solved. Extrapolating the EGRET period to their epoch, COS-B also looked at their archival data and found the signature for the pulsar. Around the same time, two VHE gamma ray groups (Durham and Ooty) also went back to their archival data and tried to look for the emission from the pulsar. Both the groups (Bowden et al, 1993,Vishwanath et al, 1993) found modest pulsar signatures with VHE gamma ray peaks coinciding with the peaks in Cos-B data. The flux reported by the Ooty group(with simultaneous observation at 2 sites for a total of 28 hours) at energy thresholds of 0.8 and 1.7 TeV was $2.1 \times 10^{-11} sec^{-1} cm^{-2}$ and $0.44 \times 10^{-12} sec^{-1} cm^{-2}$ respectively. Later, in the 90s, Geminga was looked at by the Whipple imaging device (Akerlof et.al, 1993) who did not see any signal and upper limit was given. Fig. 1(b) shows the current status of energy spectrum of Geminga Pulsar. HEGRA experiment has also given only upper limits for emission of VHE $\gamma-$ rays from Crab and Geminga pulsars. (Aharonian et al, 1999)

(c) The Vela Pulsar

Vela Pulsar is the brightest gamma ray pulsar and has been looked at for VHE gamma ray emission since the 70s. Earliest observations were at Narrabari by Grindlay et al (Grindlay et al, 1975). In two consecutive years, they saw a single pulse, coincident with the optical main pulse. However, on neither occasion the signal was strong. The Tata group working at Ooty detected pulsed emission from the Vela Pulsar in several years. Their first detection (Bhat et al, 1980) clearly showed a two peak structure in the phasogram. While the absolute phases were not available, the two peaks were separated by 0.42 phase and the combined strength of the peaks was 5σ. When the Tata group added their subsequent data for 3 years(at differing thresholds 5 to 12 TeV) (Bhat et

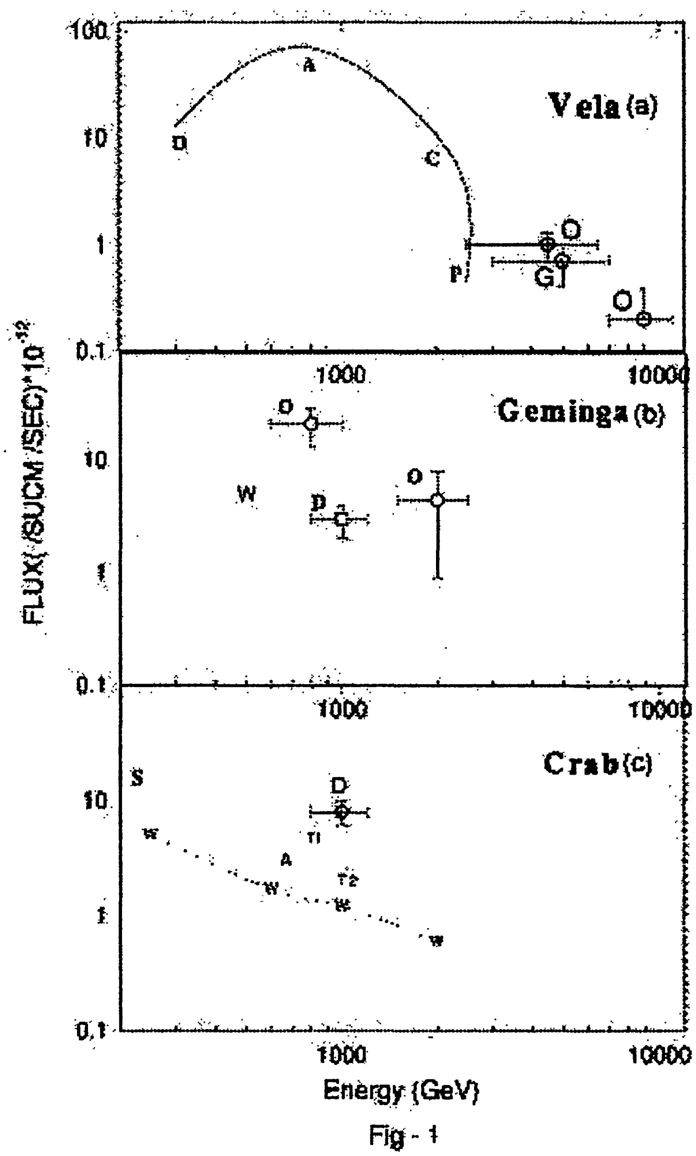

Figure 1. The energy spectrum of Vela, Geminga and Crab pulsars:(a) Vela The positive detections O and G refer to Ooty and Grindlay experiments.The curve connects all the upper limits on the pulsed fraction- D: Durham, A: Adelaide, C: Cangaroo,and P: Potschefstrrom (b) Geminga The positive detections O and D refer to Ooty and Durham experiments W is the upper limit from Whipple (c) Crab: The positive detection D refers to Curham experiment. Upper limits are - S: Stacee, W: Whipple, A: Asgat, T: Tata(Ooty),T2 Tata (Pachmarhi).

al, 1987), all of which had absolute phase information, a $> 4\sigma$ peak was detected at the Optical main position.

After the advent of the imaging techinque, the first group to look at Vela pulsar was the Cangaroo group working in Australia. They reported unpulsed emission above 2.5 TeV from the Vela region. It was also found that the peak of the emission was not centred on the nebula surrounding the pulsar but is located 8 arc minutess away southeast of the pulsar. Later, the Durham group working again in Australia but at lower energy thresholds (300 GeV) did not detect either the pulsed or the unpulsed signal from the nebula. However their upper limits are not in conflict with the Cangaroo results. Fig.1(a) shows the current status of pulsed emission from Vela Pulsar. It is important to remember that both Grindlay's and Ooty's signals were seen at the same phase as the optical main pulse.

(d) PSR 1706-44

This is one of the few pulsars where there is agreement from both the experiments which have recently looked at it. The Cangaroo group detected it first (Kifune et al, 1995) and their results were confirmed later by the Durham group (Chadwick et al , 1997) . However, neither group sees any pulsation from the object at the period given by EGRET.

(e) PSR 0355+54

This is a pulsar with low timing noise indicating high internal temperatures. The EGRET looked at it and termed it a a prime candidate for future observations. This is also the pulsar with the largest glitch ever found. The Tata group, working at Pachmarhi, observed the source in 1987 soon after the glitch and found a peak of significance 4.3σ (Bhat et al, 1990). The flux was at > 2 TeV. The next two observation seasons did not yield any time averaged signal . However, when only the events in higher rate minutes were phasogrammed, again a 4 sigma signal was seen at the same phase as in the '87 observations. There has been only a upper limit at lower energies for this object from the Whipple telescope. This is a pulsar worth further studies.

4. Recent Pachmarhi Observations on Pulsars

Many simulations, including the recent extensive calculations by Chitnis and Bhat (Chitnis and Bhat,1999) have shown that the gamma ray lateral distribution (LD) is very different from that of protons in having an almost constant density till about 120 meters where it becomes higher resulting in the so called hump region (a result of the focusing property of Čerenkov radiation) for the next 20 meters. The fall off from the hump region is similar to the monotonic decrease for the proton showers from the core. The Monte Carlo simulations with these inputs for the PACT array showed that a gamma ray event (a) would have at large values of total Cerenkov pulse height since a typical gamma ray would deposit much more Cerenkov light than a typical cosmic ray . Further β, a LD parameter which is a measure of how large the detector with the maximum pulse height would be compared to the rest of the detectors, would be useful for distinguishing between proton and $\gamma-$ ray showers.

During 1992-1994, the Tata group working at Pachmarhi ran an interim array for testing some of the hypothesis concerning LD of VHE gamma rays. 8 banks of mirrors,

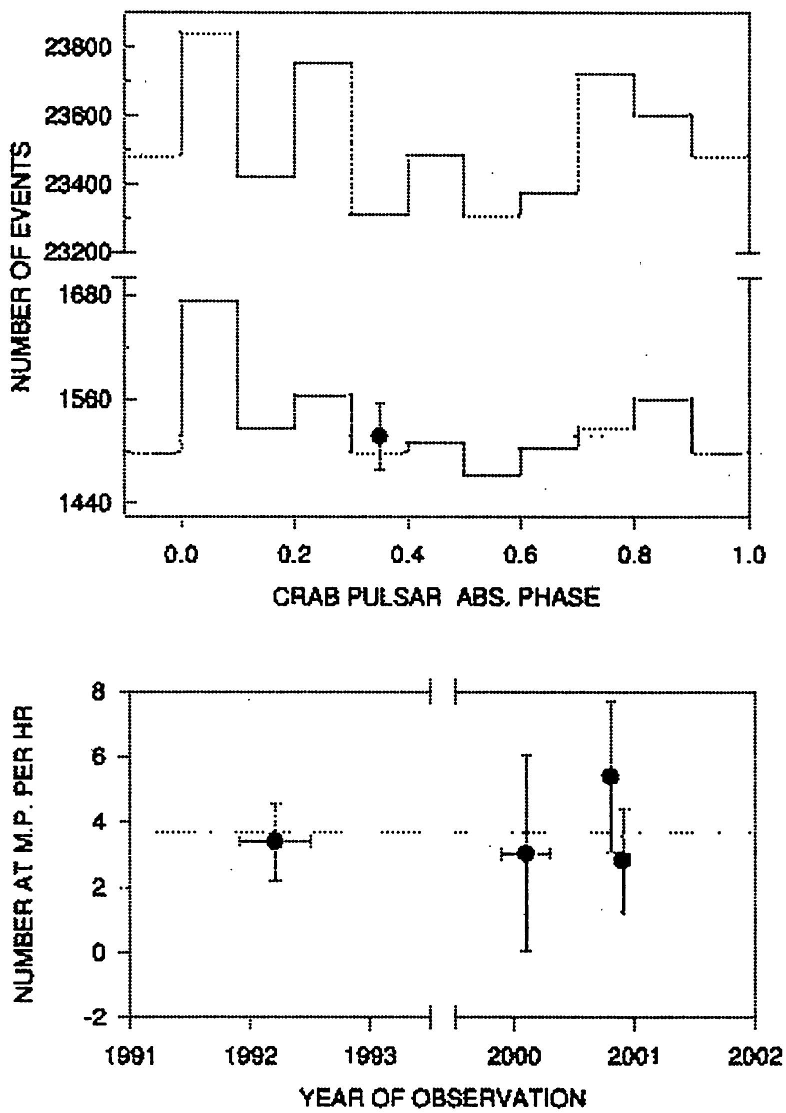

Figure 2. (a)The phasogram of events from Crab pulsar during 1999-2000. The top part is the phasogram of all events without any cuts. The bottom part is the result of several cuts (see text). (b)The rate of detected events in the Main Pulse region. The data are from the 1992 Interim array and the recent PACT experiment.

each of total area 2.5 m^2 were deployed in a field of 80m × 100m area. The exposures for Crab and Geminga were 80 and 49 hours respectively(Vishwanath, 1997). It was shown that the events at phases at which GeV emission was found(Main pulse region for Crab and around 0.6 for Geminga) displayed the same features as expected from gamma ray events. When cuts based on these parameters were applied to the data, the phasograms showed the signature of the pulsars. The number of detected gamma rays amounted to 2-3 hour at these phases. It was also shown that the excess did accumulate over time and was not confined to few runs. However, the Crab pulsar showed a much broader light curve than at GeV energies. Another interesting aspect of this analysis was that the mean Cerenkov light (measured in ADC units) was higher at these phases, an indication of the gamma ray admixture.

A totally new set up has been commissioned recently at Pachmarhi with 25 telescopes, each with 7 mirrors , having a total area of 105 sq meters of mirrors(Bhat et.al, 2001) for using both the LD aspects and the arrival direction information for the increase of sensitivity. A total of 45 hours of data from runs in Nov 1999 to Nov 2000 on Crab pulsar was taken. Fig 2(a) shows the Crab pulsar phasograms without any cut and with the cuts. It can be seen that the phasogram without any cut does not show any significant emission at any phase and an upper limit to the time averaged emission is derived above > 900 GeV as $2 \times 10^{-12} sec^{-1} cm^{-2}$. This upper limit is similar to those set by most experiments.

Since the experiment is capable of good angular resolution, cuts were applied on the space angle difference between the event and the pulsar direction . Further , a cut was imposed on the number of mirrors hit and the β parameter both of which place the events at higher energies. The peak seen at the Main Pulse phase in the lower half of Fig. 2(a) is a 4σ signal. Fig 2(b) shows the rate per hour of the events in the Main Pulse region for the 3 sub periods (1999 Nov, 2000Jan, 2000 October and 2000 November) of the data taking. Within errors, the rate is same for the 3 data periods. The mean rate is 3.4 ± 1.2 per hour which compares well with the detected rate with the interim array with similar cuts discussed above.

5. Discussion

It is certain that most of the pulsar energy spectra have to steepen in the energy range of the atmospheric Cerenkov experiments. The precise energy region of the steepening will be clear when some of the lower energy threshold experiments become fully functional. This will help in distinguishing between the PC and the OG models of gamma ray emission from pulsars.

Some comments have to be made about the results from the earlier generation experiments. Lacking detailed Monte Carlo calculations which are regular features of the present day experiments , the energy thresholds and collection area estimates would have been less precise. However, the calculations in getting the pulsar phase for the event had been well known. Some remarks are also in order about the non-reproducibility which plagued experiments in the early days when the energy thresholds of experiments were varying with constant attempts to lower the threshold. If a new component does surface at > 1 TeV energies, it is not surprising that there were conflicting results depending on the energy threshold of the experiment. Another important aspect is the possible light curves at TeV energies. While in the Egret range it self there is change in the light curves, it is not obvious what to expect at much higher energies. The various Crab pulsar phasograms shown in Rao and Sreekantan (Rao and Sreekantan, 1990) indicate that there is the likelihood of broader lightcurves at higher energies.

It is seen that the recent results from the Pachmarhi experiment do indicate a finite number of events from the Crab Pulsar. While the cuts need to be understood properly before an actual flux could be given, it would be obviously greater than the detected flux which is at the level of $7 \times 10^{-12} sec^{-1} cm^{-2}$. It should also be noted that the lcuts for the data place the events detected at energies > 1.5 to 2 TeV, much greater than the actual energy threshold of the experiment. The fact that similar flux was seen from the interim array is also interesting. The most stringent upper limits in case of Crab Pulsar have come from the Whipple Imaging telescope. A point made several years ago (C.L.Bhat et al, 1994) that the imaging technique could have biasses for sources with a flatter spectrum than that of the Crab nebula still holds good. It is also important to note that while there are many results on the Crab nebula itself, the attempts to look at the pulsar itself are rather few.

One should also remark on the very low flux levels seen in many of these pulsars, Long exposures are very necessary to detect such flux levels. Detected flux from the Crab pulsar is 2-3 per hour in the experiments of Dowthwaite et al and the recent results from the Pachmarhi experiment. This has to be compared to the flux levels of 2-3 per minute from the whole nebula. If there is a finite flux from the Crab pulsar at TeV energies, it should show up as a mild bump in the overall energy spectrum from Crab. If the nebular emisssion at few hundred GeVs is solely due to inverse Compton scattering process, a new process at TeV energies should add to the nebular flux. One should however keep in mind the very low flux from pulsar and only experiments with good energy resolution will be able to opine on this issue.

Further, when at least two experiments see the same effect at the same phase, the credibility of the overall effect should be quite high. Thus, it is possible that the earlier results from Durham as well as the new preliminary results from Pachmarhi do point to a new pulsar component at higher energies.

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