Aust. J. Phys., 1995, **48**, 305–19

The Prospects for Very High Energy Gamma Ray Astronomy*

T. Kifune

Institute for Cosmic Ray Research, University of Tokyo,
3-2-1 Midori, Tanashi, Tokyo, 188, Japan.

Abstract

Very-high-energy (VHE) gamma rays, with energies $\gtrsim 1$ TeV $= 10^{12}$ eV, are observed with ground-based telescopes using the atmospheric Čerenkov technique. This field of astronomy has recently experienced its coming of age, opening a new observational window on the universe after efforts spanning almost 30 years. Recent advances in this field have been aided by the results from satellite detectors with high-energy (HE) gamma ray 'eyes'. Satellite detectors are sensitive to HE gamma rays, up to energies of about 10 GeV $= 10^{10}$ eV. In this paper, VHE gamma ray astronomy is reviewed, and the 3·8 m diameter telescope of the Japanese–Australian CANGAROO project is used to illustrate the detection techniques. As VHE gamma ray astronomy is closely related to observations in the HE region, results from recent satellite experiments are also discussed.

1. Introduction

Gamma rays enable some of the most energetic sites of particle acceleration in the universe to be probed. Interactions between high-energy (HE) elementary particles result in the production of gamma rays, which travel with little attenuation through the interstellar medium. The universe is filled with cosmic ray particles with energies ranging from below 10^9 eV to above 10^{20} eV. Cosmic ray particles, protons or heavier nuclei, are deflected by the galactic magnetic field, and the 'memory' of their birth place is almost lost by the time they arrive at the Earth. The detection of gamma rays can tell us the sites where HE particles are accelerated and intense gamma rays produced.

A gamma ray energy of ~1 GeV is equal to the rest mass energy of nucleons, and corresponds to a temperature of about 10^{13} K if the gamma ray is produced as a result of thermal equilibrium. Such a high-temperature state is not, however, found in the present universe. Thus these gamma rays are produced by HE protons and/or electrons which have been accelerated in the galaxy by non-thermal processes. Cosmic ray protons collide with matter protons in interstellar space and/or near their acceleration sites. This process is well understood from elementary particle experiments studying the proton–proton

* Refereed paper based on a plenary lecture given to the joint Sixth Asia Pacific Physics Conference and Eleventh Australian Institute of Physics Congress held at Griffith University, Brisbane, July 1994.

0004-9506/95/020305\$05.00

reaction. Pi mesons are created as secondaries and neutral pions, π^0, decay into gamma rays. With this realisation, gamma ray astronomy was proposed by Hayakawa (1952) and Morrison (1958) to observe gamma rays produced by cosmic rays through such proton–proton collisions. We can infer the existence of HE particles far away from the earth by detecting gamma rays. Assuming that the cosmic ray intensity throughout the galaxy is the same as that locally measured at the Earth, the total thickness of matter through the galaxy can be estimated from the gamma ray flux.

Two satellites dedicated to gamma ray observation, SAS II (1972–1973) and COS B (1975–1982), detected emission along the galactic disc, in agreement with the belief that the radiation is coming from cosmic rays interacting with the interstellar medium gas. The COS B catalogue (Swanenburg *et al.* 1981) comprises 25 sources, among which the Crab and the Vela pulsar are identified by the pulsed nature of their emission (see, e.g., the review by Bignami and Hermsen 1983). The Compton Gamma Ray Observatory (CGRO), which was launched in 1991, includes on board the EGRET detector, which has uncovered several tens of Galactic and extragalactic gamma ray sources in the energy region from 100 MeV to 10 GeV.

Five galactic point sources detected by EGRET have been identified with young pulsars (rapidly rotating neutron stars), showing that the pulsars are one class of object which accelerate cosmic ray particles. Thus, gamma ray astronomy can be used to find such acceleration sites of cosmic rays and to study the acceleration mechanism. In the pulsar magnetosphere, the rotating magnetic field induces an electric field. The dynamo mechanism is thought to accelerate electrons and positrons to very high energies. High-energy electrons and positrons suffer from synchrotron radiation in the magnetic field. The inverse Compton effect, boosting ambient low-energy photons to higher energies, is another source of energy loss for the electrons and positrons. Ambient photons can, however, be boosted to gamma ray energies by this process. Soft photons cause HE gamma rays to change into electron–positron pairs, since 1 GeV gamma rays colliding with ultraviolet photons (or 1000 GeV gamma rays colliding with infrared photons) have about 1 MeV energy in the centre-of-mass reference frame, which exceeds the threshold energy of an electron–positron pair. With increasing gamma ray energy, softer photons can contribute. The pair creation occurs more efficiently at higher energies, and the maximum energy of the gamma rays produced depends on various conditions in the pulsar magnetosphere, characterised by parameters such as the strength of the magnetic field, pulsar period and the total luminosity of the pulsar. The energetic gamma ray radiation from the Crab and the Vela pulsars has been explained as a result of a cascade of these processes (Cheng *et al.* 1986). A similar cascade process of degrading energies of gamma rays and electrons also occurs in other objects, if the matter density and ambient photon density are sufficiently thick, such as at the central core of AGN (active galactic nuclei). Gamma rays can also tell us the thickness of matter and ambient photons, in addition to indicating the acceleration process and providing information on the resultant energetic particles. The matter thickness can be inferred from other methods, for example, from 21 cm radio-astronomical observations. However, this line emission comes from hydrogen atoms, and does not include contributions from molecular hydrogen or bare protons in highly ionised plasma. Radio-wave observations at millimetre wavelengths supply us with information on molecules in the galaxy (Schull 1982). The cosmic ray distribution through the Galaxy can be clarified along with a unified understanding on the distribution of galactic hydrogen atoms and molecules (Bloemen *et al.* 1984; Bhat *et al.* 1984).

The search for gamma rays with energies $\gtrsim 1000$ GeV was first attempted in the early 1960s. However, only relatively recently have VHE gamma rays been detected on a sound statistical base with a significance better than 10σ. This advance has been achieved using an 'imaging' Čerenkov telescope, a technique which has resulted in improved angular resolution and improved discrimination against the cosmic ray background.

2. Čerenkov Imaging Telescopes

The most common technique in this energy region is the Čerenkov technique, in which Čerenkov light, emitted from the electron–positron cascade initiated by the primary gamma rays in the upper atmosphere, is detected. Similarly, cosmic ray particles generate Čerenkov light and cause the major background in the counting of gamma ray events. Thus, the minimum detectable flux with a conventional Čerenkov telescope is limited by the cosmic ray background, and has been about $10^{-10}\ \mathrm{cm^{-2}\,s^{-1}}$ for energies $\gtrsim 1$ TeV. Before the imaging technique was pioneered, observers often relied upon detecting a known source periodicity (e.g. for pulsars) or evidence of sporadic enhancements in counting rate, which were ascribed to VHE gamma ray emission. A number of objects have been reported in the last decade as VHE gamma ray sources, however, mostly with only marginal statistical significance (see, e.g., the review by Weekes 1992).

The idea of the imaging Čerenkov telescope was proposed in the late 1970s (Weekes and Turver 1977; Turver and Weekes 1981). The Whipple 10 m diameter telescope employed the first imaging system and operated for more than 10 years with a 'camera' of 37 photomultiplier tubes. The Whipple group's detection of a signal from the Crab (Weekes *et al.* 1989) showed that the imaging Čerenkov telescope can reduce the cosmic ray background and have an angular resolution as good as $\sim 0{\cdot}1^\circ$. These characteristics improved the detection sensitivity of the gamma ray flux to as low as $10^{-11}\ \mathrm{cm^{-2}\,s^{-1}}$, which is *a posteriori* the level at which strong sources emit VHE gamma rays. The principle of detecting gamma rays through Čerenkov light is shown in Fig. 1. The lateral distribution of Čerenkov light is flat out to a ~ 150 m radius because the emission is within a cone of about 1° and the height of the electron–photon shower is about 10 km. Thus the detection area amounts to the order of $10^4\ \mathrm{m^2}$, which is much larger than the typical area of $1\ \mathrm{m^2}$ in satellite detection, enabling the detection of weak flux at higher energies. The image of the light measured with the telescope basically represents the 'shape' of the electron–positron cascade, which is elongated along the shower axis parallel to the direction to the star at which the telescope is aimed.

Monte Carlo simulations indicate that the image of Čerenkov light from a gamma ray shower has an elliptical shape elongated towards the source direction. A cosmic ray shower produces a broader, more irregularly shaped image. The image can be characterised by parameters such as the 'width' and 'length' of the Čerenkov light image, and the orientation of the image, α. The parameter α is the angle between the major axis of the elliptical image and the line joining the

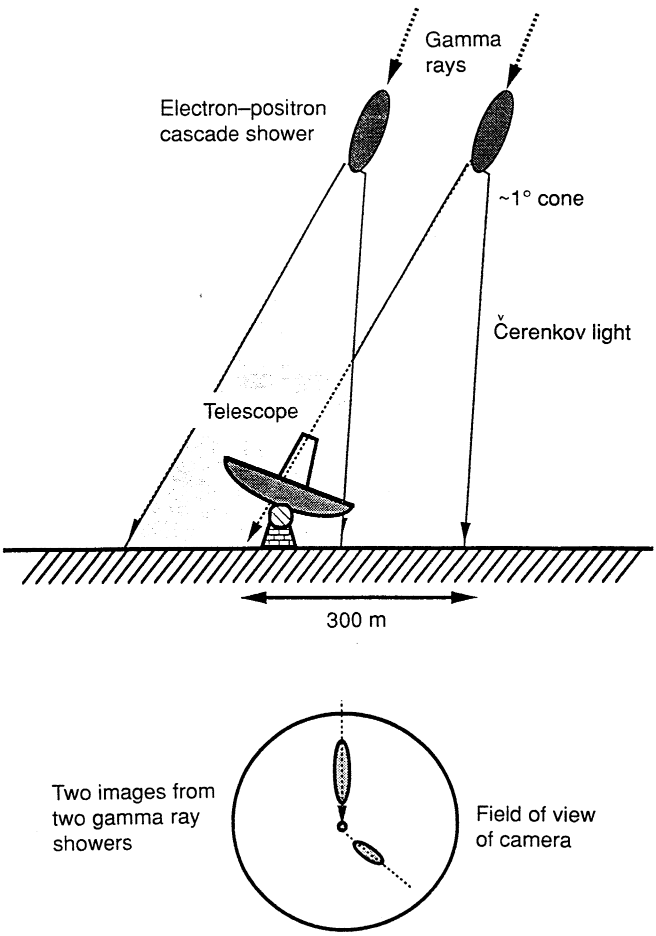

Fig. 1. The principle of detecting gamma rays through the imaging Čerenkov technique. The image of the light measured with the telescope basically represents the 'shape' of the electron–positron cascade, which is elongated along the shower axis in the direction to the star at which the telescope is aimed. Cosmic ray showers have images of a more irregular shape than the simple elliptical shape of gamma ray images. The image has a size of about 1° extension in the field of view of 3°–4° diameter, and various image parameters (see the text) can be determined with an accuracy of about 0·1°.

nominal source position (usually the centre of the field of view) to the centroid of the observed image. The detections by the Whipple group of VHE gamma rays from the Crab nebula (Weekes *et al.* 1989; Vacanti *et al.* 1991) and the active galaxy Markarian 421 (Punch *et al.* 1991) have demonstrated that the gamma ray signal can be distinguished from the cosmic ray background using the image shape and orientation. They have shown that gamma ray events from a point source appear as a peak near the origin on a flat background distribution when the event rate is plotted as a function of α. The size of this peak will be affected by the choice of the nominal source position used in the determination

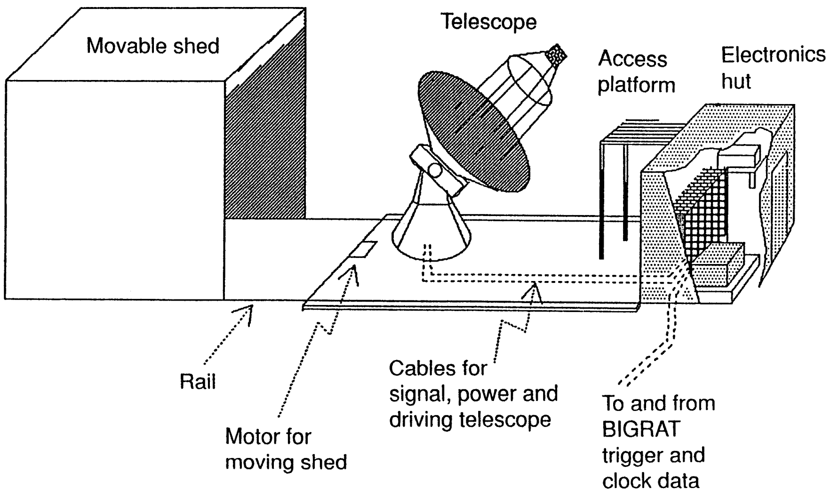

Fig. 2. Schematic of the experimental setup of the 3·8 m telescope. A camera of 220 photomultiplier tubes is set in the focal plane of the 3·8 m telescope. The output signal from each tube is sent via 30 m of coaxial cable to the adjacent electronics hut, data-processed under computer control, and recorded on 8 mm video tape.

of α, so that the position of a gamma ray point source within the field of view can be determined to an accuracy of $\sim 0 \cdot 1°$.

The supernova explosion in the Large Magellanic Cloud in 1987 gave a group of Japanese institutions the opportunity of joining VHE gamma ray astronomy with a 3·8 m telescope, which had been used by optical astronomers and has a better surface quality than the other contemporary Čerenkov telescopes. The CANGAROO (Collaboration between Australia and Nippon for a GAmma Ray Observatory in the Outback) Project (Patterson and Kifune 1992) was proposed at the end of 1988. The project makes 'stereoscopic' observations of Čerenkov light with two imaging telescopes, the 3·8 m telescope (Hara *et al.* 1993) and BIGRAT, the telescope of the University of Adelaide. Fig. 2 illustrates the experimental set up of the 3·8 m telescope, at the site near Woomera, South Australia. BIGRAT is described in detail elsewhere (e.g. Edwards *et al.* 1992). The focusing accuracy of the 3·8 m telescope is good enough to measure the image of Čerenkov light with an accuracy of better than $0 \cdot 1°$. The 3·8 m telescope is equipped with a multi-pixel camera of 220 photomultiplier tubes, each of which views a $0 \cdot 12° \times 0 \cdot 12°$ area of the sky, with a total camera field of view of about 3°. The camera measures the number of photoelectrons and the pulse arrival time in each tube.

The CANGAROO 3·8 m telescope has a smaller area than the 10 m of the Whipple instrument but uses a smaller, by a factor of two, camera pixel size for measuring the image. Data recorded with this telescope show that a camera of good resolving power has an efficient capability of discriminating against the night-sky background photons, and discriminating cosmic ray background events from genuine gamma ray events. The 3·8 m telescope has a $\sim$1 TeV threshold for detecting gamma rays. Further upgrading of the imaging telescope would decrease

Table 1. Number of gamma ray sources detected by EGRET
Upper limits for 86 selected pulsars and 460 selected active galactic nuclei

Statistical significance of detection	Pulsars	Unidentified objects at low galactic latitudes ($b < 10°$)	Normal galaxy	Active galaxy	Unidentified objects at high galactic latitudes ($b > 10°$)
$>6\sigma$	5	10	1 (LMC)	25	8
$(5\text{–}6)\sigma$		27		13	35

the threshold energy to ~100 GeV. The total number of imaging Čerenkov telescopes now amounts to about ten, including the ones under construction or in the planning stage.

3. CGRO EGRET Results as a Guide

The number of GeV gamma ray sources reported by the EGRET team (Fichtel *et al.* 1994) now exceeds 100, much larger than the 25 from the COS B catalog (Swanenburg *et al.* 1981). The EGRET results are summarised in Table 1. The EGRET sources are the most likely candidates for VHE gamma ray sources. However, most of them do not show a pulsed nature or, at least, a known period. A clear means of identifying gamma ray sources with known objects at other wavelengths is the detection in the gamma ray data of modulation at the same period as observed at other wavelengths. The five pulsars are good examples, as their modulated gamma ray emission has enabled them to be identified with radio and/or X-ray pulsars. Unsuccessful searches were made for gamma rays from 86 other pulsars, and upper limits set on the respective gamma ray fluxes. One of the main efforts of VHE gamma ray experimental studies is the search for VHE emission from these gamma ray pulsars.

Several EGRET galactic sources show complex structure suggestive of multiple sources or extended source nature. Electrons are likely to be the progenitor of gamma rays from gamma ray pulsars but protons are the more likely progenitor for these galactic sources of extended/complex structure. Analysis of extended sources is comparatively more difficult than for point sources, both in the HE and VHE regions. The angular resolution of ~$0\cdot 1°$ of the VHE imaging telescope must be sufficient to identify the emission region.

The COS B satellite discovered only one extragalactic gamma ray source, the AGN 3C 273. This number has dramatically increased following EGRET observations. It is not easy to explain the origin of the luminous HE gamma rays observed from AGNs. AGNs have a compact active region, presumably with a massive black hole at the centre. The region is surrounded by a thick shell of soft photons which degrade the energy of particles and prevent HE gamma rays from escaping. An economical mechanism involving the relativistic flow of matter in the AGN jet was proposed (Dermer *et al.* 1992) to explain the observed GeV gamma ray fluxes. The gamma ray energy spectra from AGN can be approximated by power laws with observed power-law indices distributed around −2. Most of the spectra extend without a break up to about 10 GeV. However, many theoretical calculations predict a cutoff at several tens of GeV to ~100 GeV for most of the sources. The detection of the maximum energy of the emission, throwing light on the gamma ray production mechanism, can only be done by VHE gamma ray astronomy.

4. Recent Results in VHE Gamma Ray Astronomy

The 10 m imaging Čerenkov telescope of the Whipple group was used to detect VHE gamma rays from the Crab nebula and from the active galaxy Markarian 421. Following its detection by the Whipple group, many groups have observed the Crab nebula. The spectrum initially reported by the Whipple group (Vacanti *et al.* 1991) was revised (Lewis *et al.* 1993) to a somewhat lower energy spectrum, which is given by

$$\frac{\mathrm{d}N(E)}{\mathrm{d}E} = (1\cdot 48 \pm 0\cdot 09 \pm 0\cdot 41) \times 10^{-7} \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-2\cdot 69 \pm 0\cdot 09 \pm 0\cdot 3} \text{photons m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}.$$

Observations of the Crab were made with the CANGAROO 3·8 m telescope at the relatively large zenith angles of $53 - 60°$. Since the Crab is located in the northern sky, these low elevation angles are at the culmination of the Crab as seen from Woomera. Such large zenith angles lead to a higher threshold energy, however, with a larger detection area than at the zenith (Sommers and Elbert 1987). A flux of $(7\cdot 6 \pm 1\cdot 9) \times 10^{-13}$ photons $\mathrm{m}^{-2}\,\mathrm{s}^{-1}$ was observed above 7 TeV (Tanimori *et al.* 1994), which is in agreement with the above Whipple flux. The spectrum initially reported by the THEMISTOCLE group in France was higher than the original Whipple spectrum (Baillon *et al.* 1993). Recently, recalibration of their telescope characteristics by simulations and a subsequent reanalysis of their data has resulted in a spectrum more consistent with the revised Whipple spectrum (P. Goret, personal communication 1994). The HEGRA group has also given preliminary reports of a positive detection of $6\cdot 2\sigma$ emission from the Crab (F. Krennrich 1994). Thus VHE gamma ray emission from the Crab has been confirmed by a number of groups. However, the data reduction procedure of each group needs to be more carefully examined. For this purpose, the Crab is now used as the standard candle for which VHE gamma ray astronomy has long waited. The component of VHE gamma rays in phase with the pulsar period of the Crab pulsar seems, from the data of imaging telescopes, to be much weaker than the unpulsed component. Some claims for a strong periodic component have been reported by other workers but have not yet been substantiated.

The possibility that other EGRET pulsars are VHE gamma ray sources has also been examined. The 3·8 m imaging Čerenkov telescope of CANGAROO commenced operation in 1992, and has found evidence of TeV gamma rays from PSR 1706–44. This pulsar was detected by COS B, although only identified subsequently as a radio pulsar, and then identified as a gamma ray pulsar by the EGRET detector (Thompson *et al.* 1992). Fig. 3 is the α distribution for PSR 1706–44, observed with the CANGAROO 3·8 m telescope during the period of July and August 1993 (Kifune *et al.* 1993, 1994). Shown also are the Whipple detection of gamma ray signals from (a) Markarian 421 and (b) the

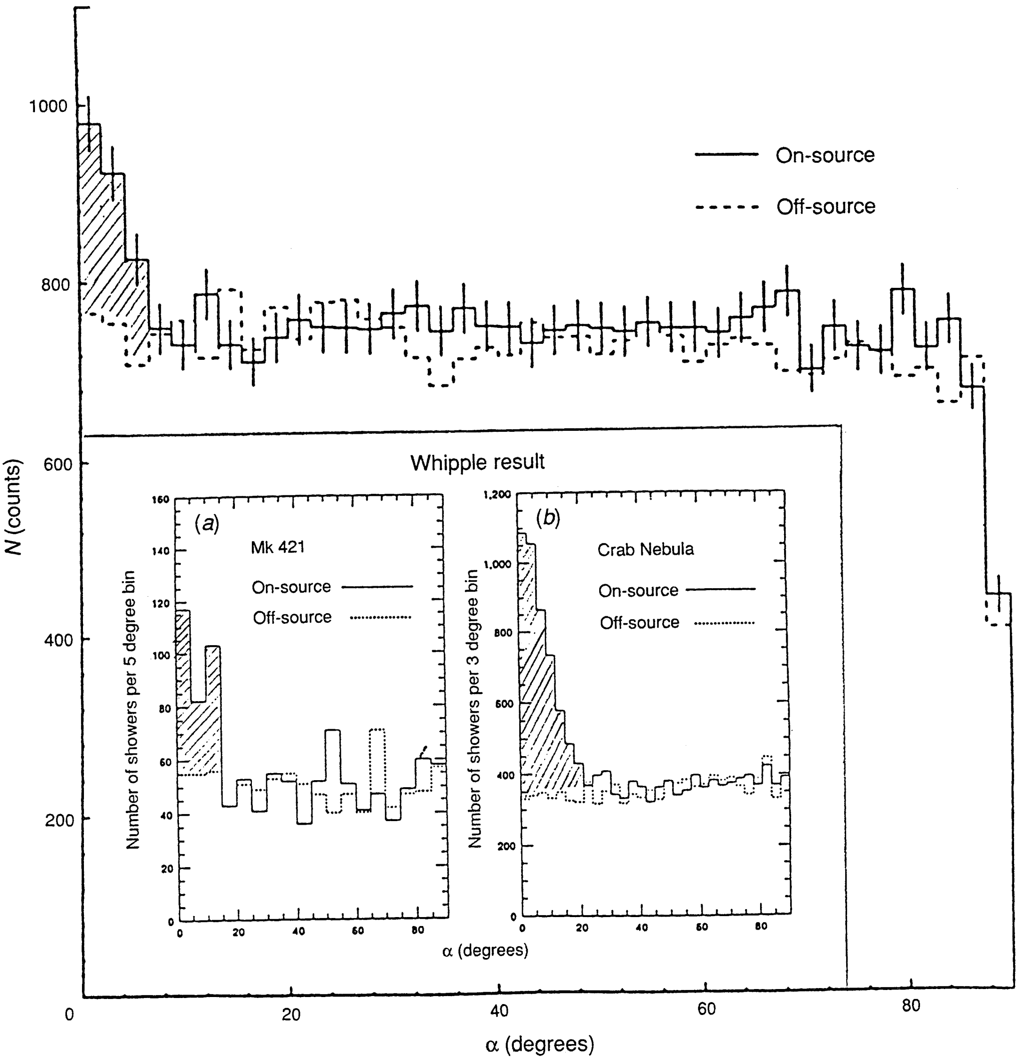

Fig. 3. Evidence of detecting gamma rays from the CANGAROO data on PSR 1706–44. The data shown are from observations in 1993. The Whipple detections of gamma ray signals from (a) Markarian 421 and (b) the Crab (from Punch *et al.* 1991) are also shown in the lower part. The number of events is plotted as a function of α, the orientation angle of the Čerenkov image. The Čerenkov image of gamma ray showers is elongated toward the direction of the gamma ray source in the image plane, so that gamma ray events from a point source have orientation angles near zero, causing a peak at $\alpha = 0°$. The effect was detected and is shown by shading the peak of excess events. The solid and dashed lines indicate on-source and off-source data respectively.

Crab nebula. The horizontal axis is the orientation angle α of the Čerenkov image. The comparison of observed event rate is made between the case where the gamma ray source lies within the field of view of the telescope (on-source case, indicated by solid line) and that where the source is out of the field of view (off-source case, by dashed line in the figure), and an excess of events at $\alpha \sim 0°$ is considered to be due to gamma rays.

Three other pulsars have been detected at satellite energies: Vela, Geminga and PSR 1055–52. Searches for VHE gamma ray emission from the Vela pulsar have generally concentrated on the search for a periodic signal (see e.g. Edwards *et al.* 1994 for a review). No convincing evidence for pulsed emission has been found. Searches using the imaging technique for pulsed and/or unpulsed emission are proceeding. There are several experiments which suggest pulsed emission from Geminga (Bowden *et al.* 1993; Vishwanath *et al.* 1993). The only available data recorded with an imaging Čerenkov telescope were those of the Whipple group, who set an upper limit for Geminga smaller than the Crab flux (Akerlof *et al.* 1993). PSR 1055–52 is the most recently detected EGRET pulsar, and observations at very high energies are still at an early stage.

The BL Lacertae-type AGN Markarian 421 is the nearest AGN detected by EGRET, and is to date the only AGN from which VHE gamma rays have been observed. This fact, however, indicates that in at least one AGN, VHE gamma rays are emitted at energies above 1 TeV, encouraging efforts of finding more VHE sources. Recently, the Whipple group detected a rapid increase in the VHE emission from this object (Kerrick *et al.* 1994). Increased activity was confirmed at X-ray energies by the satellite ASCA (Takahashi *et al.* 1994). This observation of time variability at these energies has important implications for models of VHE gamma ray emission from this class of objects.

5. Prospects for VHE Gamma Ray Astronomy

(5a) *Gamma Ray Pulsars and Synchrotron X-ray Nebulae*

The detection from the Crab nebula of unpulsed VHE gamma rays, with no significant pulsed component, suggests that the major emission site changes from the pulsar magnetosphere at GeV energies to the nebula in the 100 GeV to 1 TeV energy region. The preliminary result from CANGAROO data on PSR 1706–44 also appears to show that the major fraction of the detected signal is unpulsed. In the Crab nebula, X-ray emission is from synchrotron radiation by energetic electrons, whereas gamma rays are expected from the inverse Compton effect of the same progenitor electrons hitting ambient soft photons in the nebula (see e.g., De Jager and Harding 1992). An alternative model has been proposed by Kwok *et al.* (1991), who explain the steady emission of VHE gamma rays as coming from a compact region, a couple of light cylinder radii from the pulsar.

The radio and X-ray luminosities, or at least upper limits, are known for the (possible) nebula associated with the gamma ray pulsars, as shown in Table 2. According to the model for the Crab, in which VHE gamma rays are emitted from the nebula, the X-ray luminosity and TeV gamma ray luminosity energy outputs from the two competing processes of synchrotron radiation and the inverse Compton effect must be explained in a consistent way, depending on the strength of the magnetic field and the density of ambient photons. It is thus interesting to compare the luminosities in VHE gamma rays and X-rays in other pulsars such as Vela and PSR 1706–44. For this purpose, a tentative estimate is given in the following with a very simplified view of approximating the density of ambient photons only by the $2{\cdot}7$ K microwave background density. The photon density

Table 2. Nebula emission

Object	B (μG)	Luminosity (erg s^{-1}) 1 GHz	0·1–2·4 keV	4 keV
Crab	250	$4\cdot6\times10^{33}$	2×10^{37} (0·2–4 keV)	$6\cdot2\times10^{36}$
Vela	15	$3\cdot0\times10^{32}$	$2\cdot7\times10^{33}$	
1706–44	?	$(0\cdot5–2)\times10^{29}$	1×10^{32}	
1055–52			$<7\cdot5\times10^{32}$	

in a nebula with a given observed luminosity decreases with increasing nebula size. The size of the Crab nebula is about 1 pc, and with this size the total photon density is of a similar order of magnitude as the 2·7 K photon density. Estimates based on this view will not be very far from reality unless the nebula size is much smaller than 1 pc. With these assumptions, the ratio of the two energy outputs from the inverse Compton effect, $P_{\rm ic}$, and the synchrotron effect, $P_{\rm sync}$, is approximated by

$$P_{\rm ic}/P_{\rm sync} = 6\times10^{-12}/B^2\,,$$

where the magnetic field, B, is in gauss. Taking the TeV gamma ray flux to be $\sim1\times10^{-11}$ cm^{-2} s^{-1}, for the Crab and PSR 1706–44, and assuming the same for the Vela pulsar (which if it is unpulsed, as assumed here, would not have been detected yet) the TeV luminosity $P_{\rm TeV}$ is calculated for these three objects and listed in Table 3. The ratio R of synchrotron and inverse Compton luminosities is calculated from the above formula. From this value of R and by equating $P_{\rm ic}$ with $P_{\rm TeV}$, an estimate of $P_{\rm sync}$ is obtained from $R\,P_{\rm TeV}$. The typical energy of synchrotron photons from the progenitor electrons responsible for 1 TeV gamma rays is given by $k^0_{\rm sync}$ in Table 3.

Table 3. Comparison with TeV emission

Object	B (μG)	d (kpc)	$k^0_{\rm sync}$ (keV)	$P_{\rm TeV}$ (erg s^{-1})	$R=P_{\rm sync}/P_{\rm ic}$	$RP_{\rm TeV}$ (erg s^{-1})
Crab	250	2	1·3	4×10^{33}	1×10^{4}	4×10^{37}
Vela	15	0·5	0·05	$2\cdot3\times10^{31}$	40	9×10^{32}
PSR 1706–44	>3	1·5	>0·01	$2\cdot5\times10^{33}$	>1·5	$>4\times10^{33}$

When we compare $R\,P_{\rm TeV}$ in Table 3 with the observed value in Table 2, it appears that the VHE gamma ray emission from the nebula can be consistent with X-ray emission for the Crab and Vela. The magnetic fields in Table 2 are from the estimation by De Jager and Harding (1992) for the Crab, and that by Willmore *et al.* (1992) for Vela. In the case of PSR 1706–44, the magnetic field of the interstellar medium ($\sim$3 μG) is assumed in the calculation as the lowest limit. Even with this value, the X-ray emission suggested by the ROSAT satellite (Becker *et al.* 1992) is much smaller than that expected from TeV gamma ray emission. At any rate, a much weaker magnetic field than those in Vela and the Crab is thus preferred to reconcile the situation, and this may imply that the characteristic energy of synchrotron radiation is softer than that of the X-rays measured with ROSAT.

Another possibility is that the density of ambient photons is much greater than that of the $2{\cdot}7$ K background, implying that the nebula size is much smaller than 1 pc. More careful treatments are undoubtedly necessary, but the present result for PSR 1706–44 can be interpreted in favour of the model of emission from a compact region near the pulsar. Emission of unpulsed VHE gamma rays from the Vela nebula ($\sim 10^{-11}$ cm^{-2} s^{-1}) appears quite likely, with an emission mechanism similar to that assumed for the Crab nebula.

(5b) Young Pulsars and Supernova Remnants

Supernova remnants are believed to be the acceleration site of most cosmic rays with energies below $\sim$100 TeV, and are therefore very likely to be gamma ray sources. The exponent of the power-law energy spectrum of cosmic rays is determined from the standard shock acceleration theory and, when observed at the Earth, has an extra factor of $\sim -0{\cdot}4$ added to account for the fraction of cosmic rays escaping from the Galaxy. However, the cosmic rays at the acceleration site do not suffer from this escape factor. Thus the gamma ray energy spectrum is expected to have a power exponent of about $-2{\cdot}0 \sim -2{\cdot}2$, hard enough, when extrapolated to the VHE region from the GeV energy region of the satellite detection, that the estimated flux at $\sim$100 GeV is above the detection sensitivity of imaging telescopes (Drury *et al.* 1993; F. Takahara *et al.*, personal communication 1994).

Since COS B discovered about 20 unidentified gamma ray sources, young pulsars and/or supernova remnants (SNRs) have been searched for in the (typically $\sim 1^\circ$ radius) error circles of these sources. The number of possible associations of pulsar and SNR has increased to about 20 (see e.g. Caraveo 1993) from the few, such as the Crab and Vela, which have been known for more than a decade. In Table 4 such associations from which gamma rays are detected with EGRET/COS B detectors or for which upper limits on the pulsed component have been reported are listed. The established pulsars, the Crab, Vela and PSR 1706–44, are not included in the table. It should be noted that some of the pulsars are required to have large velocities (>1000 km), and this may cast some doubt on the claimed association between the two.

In some of the EGRET source error circles, giant molecular clouds exist as well as pulsars and SNRs. The $\sim 0{\cdot}1^\circ$ angular resolution of imaging Čerenkov telescopes will enable us to identify which, if either, of these is responsible for any VHE gamma ray emission. Although the EGRET data already exclude the possibility of intense pulsar emission in some of the objects in Table 4, the unpulsed nature of VHE gamma rays may lead to the detection of a signal from such pulsars. Most of the objects appearing in Table 4 are located near the galactic centre. Along the galactic plane, the diffuse radiation is highly structured, and the EGRET analysis is sensitive to the modelling of the diffuse gamma rays (Fichtel *et al.* 1994). Thus, there may be some excess at low levels from these objects, where uncertainty in the diffuse/extended emission exists. It is interesting to consider whether pulsar emission has a major contribution and, if so, how this emission from pulsars is related to neighbouring extended emissions which is very likely from cosmic ray protons. The acceleration of protons in pulsars adds a quite new dimension to the current situation where gamma rays from the five young pulsars are considered to arise from electron acceleration.

Table 4. SNR associated with pulsars

SNR	Pulsar	P, $\dot{P}$[A]	$\dot{E}$[B]	τ[C] (10^4 yr)	d[C] (kpc)	EGRET flux[D]	γ ray detection[E]
G308·8–01	1338–62	193	1·4	1·2	8·1	<3·5	
		253		3·25	6·9		
MSH15–52	1509–58	150	18	0·15	4·4	<5·3	
		1540		1	4·2		
Kes 32?	1610–50	231	1·6	0·75	7	<3·7	
		492		0·5	5		
MSH17–39	1737–30?	607	0·07	20	3	<5·5	2CG359–00?
(G357·7–010)		466		18			
G5·4–1·2	1757–24	125	2·6	1·5	3·5	<2·8	
	(1758–24)	128		1·4(14)	~5(6)		
G6·4–0·1	1758–23?	415	0·06	5·8	10–17	<4·3	2CG006–00
(W28)		113		12	2·5	7·0±0·9	J1758–23
W30	1800–21	134	2·2	1·6	5·2	<5·1	
G8·7–0·1		134		1·6	5·5		
?	1823–13	101	2	2·2	5	<3·4	
		72				7·5±1·0	J1823–12
W44	1853+01	267	0·4	2	3·3	<2·9	
		208		>1	3·1	7·0±0·9	J1853+01

[A] Upper value indicates period (ms) and lower value the period derivative in 10^{-15} s s^{-1}.
[B] Spin-down energy loss in units of 10^{36} erg s^{-1}.
[C] Upper value for pulsar and lower for SNR.
[D] Upper value for upper limit on pulsar and lower for unpulsed, in units of 10^{-7} cm^{-1} s^{-1}.
[E] Upper value for COS B and lower for EGRET detection.

(*5c*) *Extragalactic sources*

VHE gamma rays collide with infrared photons in extragalactic space to create electron–positron pairs and thus suffer from serious absorption for distances more than several hundred Mpc (Stecker *et al.* 1992). It is therefore not surprising that the only EGRET AGN detected to date is the closest one: Markarian 421. The number of EGRET sources of AGN with small redshift is limited. The search for VHE gamma rays must be done from such objects, and it might be too early to discuss extragalactic sources when we have only one in the VHE region.

The EGRET catalogue also includes a number of unidentified sources, which may not be very distant from the Galaxy. The total luminosity of diffuse gamma rays from our own Galaxy is $(1–2)\times10^{39}$ erg s^{-1} for >100 MeV (Bloemen 1989). By assuming the energy spectrum of cosmic rays, the luminosity in VHE energies greater than 100 GeV is as large as 10^{37} erg s^{-1} and, at 1 Mpc distance, corresponds to about 10^{-12} photons s^{-1} cm^{-2}, which is not very far below the current sensitivity of imaging telescopes. Thus, it is not unlikely that some nearby galaxies contain cosmic rays intense enough compared with our own to be detectable at VHE gamma rays energies. Chi and Wolfendale (1993) showed that an extragalactic origin for cosmic rays is not compatible with the EGRET observations of the LMC, implying that the intensity varies from galaxy to galaxy.

Although VHE gamma rays are converted into electron–positron pairs while travelling vast distances, the energetic electrons and positrons inverse Compton scatter $2{\cdot}7$ K photons. In this way, HE gamma rays are generated and a halo of gamma rays is formed around the direction to the source, as discussed by a number of authors (e.g. Protheroe and Stanev 1992; Aharonian *et al.* 1993). This halo of gamma rays has a geometrical scale of ~ 100 Mpc, and a time scale of $\sim 10^8$ years, comparable to the expected lifetime of an AGN. The AGN which are gamma ray quiet at present can be accompanied by a halo of HE gamma rays. It was reported (Hartman *et al.* 1993) that there are several regions of sky from which the number of detected gamma ray events increases steadily when a number of EGRET observation periods are added together. This is in contrast to the case of time-variable AGNs for which the statistical significance decreases (due to the time variability) after this procedure of summing all the data. This may represent evidence that these halo gamma rays have been detected in EGRET data.

6. Discussion and Summary

The three sources of VHE gamma rays for which we have detections of high statistical significance are also gamma ray sources in the GeV energy region measured with the satellite-borne detectors COS B and/or CGRO EGRET. This fact indicates that the ground-based detection of VHE gamma rays with imaging Čerenkov telescopes has now reached a viable sensitivity to compete with the satellite detectors in the GeV region.

The emission from X-ray synchrotron nebula has been known to be the main contributor of VHE gamma rays in the case of the Crab. This view should be examined with the other gamma ray pulsars, but more observational data are necessary about the intensity at optical to X-ray wavelengths and the size of the nebula. The association of PSR 1706–44 with a SNR was reported by McAdam *et al.* (1993). The pulsar is located at the edge of an arc-shaped radio emission region. Further study at ultraviolet and X-ray energies is necessary in order to further the debate about an accompanying nebula. In the case of the other gamma ray pulsars, Geminga and PSR 1055–52, no associated SNR has been found, and no X-ray nebula either. X-rays from Geminga (Halpern and Ruderman 1993) are consistent with thermal emission from the neutron star surface, which may imply that it is unlikely that the emission mechanism for VHE gamma rays from the Crab also applies to Geminga. It has been reported by Ogelman and Finley (1993) that ROSAT data suggest the coexistence of thermal and non-thermal X-rays from PSR 1055–52.

At least a full month's observation (20–30 hours) is needed to obtain significance for a source of flux $10^{-11}\ \mathrm{cm^{-2}\,s^{-1}}$. It is thus very necessary to choose carefully the targets for observation and to be aware of the results at other wavelengths, as well being guided by theoretical considerations. However, it must be kept in mind that the history of astronomy at other wavelengths shows that there is the strong possibility of the discovery of serendipitous sources which theories cannot predict. It is likely that the present number of VHE gamma ray sources is limited not by the present sensitivity, but by the finite time of searching those objects from which we can expect emission. For instance, the search for VHE gamma rays from AGN is far from complete; the observation times obtained to date are still as small as 10 hours for most of the objects and the number of EGRET AGN at near distances is limited.

It may be the case that there are more gamma ray pulsars which do not emit a GeV gamma ray beam towards us but do emit unpulsed VHE gamma rays in all directions. This possibility is compatible with the characteristics so far known about the unidentified Galactic sources of CGRO EGRET. From extragalactic objects, VHE gamma rays collide with infrared photons in intergalactic space and are converted into electron–positron pairs. The absorption of gamma rays through this process becomes significant above 100 GeV. It is worth noting that the HE electrons and positrons will, in collision with $2 \cdot 7$ K photons, form secondary halos of gamma rays around the original source, and such an effect may have already been detected by EGRET. The typical energy of gamma rays of these halos ranges from 1–100 GeV depending on the primary gamma ray energy of about 1–10 TeV. Detection of such a halo at GeV energies implies original emission at TeV and a halo at TeV indicates original PeV activity.

The features of VHE gamma rays in the case of the Crab suggest a change of emission mechanism between the GeV and 100 GeV energy regions. In order to detect more extragalactic sources from as far as possible, and also to fill in the existing gap between ground-based experiments and the satellite detection, it is necessary to reduce the threshold energy of detectable gamma rays down to the ~100 GeV energy region. This is the aim of the next generation of Čerenkov telescopes.

Acknowledgment

I thank P. G. Edwards for his careful reading of the manuscript and for comments and advice which have brought about this final form.

References

Aharonian, F. A., Coppi, P. S., and Volk, H. J. (1993). Preprint presented to Maryland GRO Symposium, September 1993.
Akerlof, C. W., *et al.* (1993). Proc. 23rd Int. Conf. on Cosmic Rays, Calgary, **1**, p. 305 (University of Calgary: Calgary).
Baillon, P., *et al.* (1993). *Astroparticle Phys.* **1**, 341.
Becker, W., *et al.* (1992). IAU Circular **5554**.
Bhat, C. L., Mayer, C. J., and Wolfendale, A. W. (1984). *Astron. Astrophys.* **140**, 284.
Bignami, G. F., and Hermsen, W. (1983). *Ann. Rev. Astron. Astrophys.* **21**, 67.
Bloemen, J. B. G. M. (1989). *Ann. Rev. Astron. Astrophys.* **27**, 469.
Bloemen, J. B. G. M., *et al.* (1984). *Astron. Astrophys.* **135**, 12.
Bowden, C. C. G., *et al.* (1993). *J. Phys.* G **19**, L29.
Caraveo, P. A. (1993). *Astrophys. J. Lett.* **415**, L111.
Cheng, K. S., Ho, C., and Ruderman, M. (1986). *Astrophys. J.* **300**, 522.
Chi, X., and Wolfendale, A. W. (1993). *J. Phys.* G **19**, 795.
De Jager, O. C., and Harding, A. K. (1992). *Astrophys. J.* **396**, 161.
Dermer, C. D., Schlickeiser, R., and Mastichiadis, A. (1992). *Astron. Astrophys.* **256**, L27.
Drury, L. O'C., Aharonian, F. A., and Volk, H. J. (1993). Proc. 23rd Int. Conf. on Cosmic Rays, Calgary, **1**, p. 455 (University of Calgary: Calgary).
Edwards, P. G., *et al.* (1992). *Proc. Astron. Soc. Aust.* **10**, 27.
Edwards, P. G., *et al.* (1994). *Astron. Astrophys.*, in press.
Fichtel, C. E., *et al.* (1994). *Astrophys. J. Suppl.*, **94**, 551.
Halpern, J. P., and Ruderman, M. (1993). *Astrophys. J.* **415**, 286.
Hara, T., *et al.* (1993). *Nucl. Instr. Meth.* A **332**, 300.

Hartman, R. C., *et al.* (1993). Proc. 23rd Int. Conf. on Cosmic Rays, Calgary, **1**, p. 164 (University of Calgary: Calgary).
Hayakawa, S. (1952). *Prog. Theor. Phys.* **8**, 517.
Kerrick, A. D., *et al.* (1994). IAU Circular **5996**.
Kifune, T., *et al.* (1993). IAU Circular **5905**.
Kifune, T., *et al.* (1994). *Astrophys. J. Lett.*, in press.
Kwok, P. W., Cheng, K. S., and Lau, M. M. (1991). *Astrophys. J.* **379**, 653.
Lewis, D. A., *et al.* (1993). Proc. 23rd Int. Conf. on Cosmic Rays, Calgary, **1**, p. 279 (University of Calgary: Calgary).
McAdam, W. B., Osborne, J. L., and Parkinson, M. L. (1993). *Nature* **361**, 516.
Morrison, P. (1958). *Nuovo Cimento* **7**, 858.
Ogelman, H., and Finley, J. P. (1993). *Astrophys. J. Lett.* **413**, L31.
Patterson, J. R., and Kifune, T. (1992). *Aust & New Zealand Physicist* **29**, 58.
Protheroe, H. J., and Stanev, T. (1992). Proc. Int. Workshop on Towards a Major Atmospheric Čerenkov Detector (Eds P. Fleury and G. Vacanti), p. 103 (Frontieres: Paris).
Punch, M., *et al.* (1991). *Nature* **358**, 477.
Schull, J. M. (1982). *Ann. Rev. Astron. Astrophys.* **20**, 163.
Sommers, P., and Elbert, J. W. (1987). *J. Phys.* G **13**, 553.
Stecker, F. W., De Jager, D. C., and Salamon, M. H. (1992). *Astrophys. J. Lett.* **390**, L49.
Swanenburg, B. N., *et al.* (1981). *Astrophys. J.* **243**, L69.
Takahashi, T., *et al.* (1994). IAU Circular **5993**.
Tanimori, T., *et al.* (1994). *Astrophys J. Lett.* **429**, L61.
Thompson, D. J., *et al.* (1992). *Nature* **359**, 615.
Turver, K. E., and Weekes, T. C. (1981). *Phil. Trans. R. Soc. London* A **301**, 615.
Vacanti, G., *et al.* (1991). *Astrophys J.* **377**, 467.
Vishwanath, P. R., *et al.* (1993). *Astron. Astrophys.* **267**, L5.
Weekes, T. C. (1992). *Space Science Reviews* **59**, 315.
Weekes, T. C., and Turver, K. E. (1977). Proc. 12th Eslab Symp. (Frascati), **ESA SP-124**, p. 279.
Weekes, T.C., *et al.* (1989). *Astrophys. J.* **342**, 379.
Willmore, A. P., *et al.* (1992). *Mon. Not. R. Astron. Soc.* **254**, 139.

Manuscript received 7 July, accepted 20 September 1994