

VERY HIGH ENERGY GAMMA RAYS FROM THE VELA PULSAR DIRECTION

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ABSTRACT

We have observed the Vela pulsar region at TeV energies using the 3.8 m imaging Čerenkov telescope near Woomera, South Australia between January 1993 and March 1995. Evidence of an unpulsed gamma-ray signal has been detected at the 5.8σ level. The detected gamma-ray flux is $(2.9 \pm 0.5 \pm 0.4) \times 10^{-12}$ photons $\text{cm}^{-2} \text{sec}^{-1}$ above 2.5 ± 1.0 TeV and the signal is consistent with steady emission over the two years. The gamma-ray emission region is offset from the Vela pulsar position to the southeast by about $0^\circ.13$. No pulsed emission modulated with the pulsar period has been detected and the 95 % confidence flux upper limit to the pulsed emission from the pulsar is $(3.7 \pm 0.7) \times 10^{-13}$ photons $\text{cm}^{-2} \text{sec}^{-1}$ above 2.5 ± 1.0 TeV.

Subject headings: gamma rays: observations — ISM: individual (Vela SNR) — ISM: magnetic fields — pulsars: individual (Vela pulsar) — supernova remnants

1. Introduction

It is highly likely that high energy particles are accelerated by non-thermal processes in the vicinity of pulsars, and extensive searches have been made for very high energy (VHE; typically at the TeV energy) gamma rays from this class of objects (Kifune 1996; references therein). Positive evidence has been obtained for the Crab (e.g. Weekes *et al.* 1989; Vacanti *et al.* 1991; Tanimori *et al.* 1994) and PSR B1706 – 44 (Kifune *et al.* 1995) using the technique of imaging Čerenkov light from extensive air showers which VHE gamma rays initiate in the upper atmosphere. The Vela pulsar, PSR B0833 – 45, is one of the 100 MeV gamma-ray pulsars detected by EGRET of the *Compton Gamma Ray Observatory*, together with the Crab and PSR B1706 – 44 (e.g. Ramanamurthy *et al.* 1995).

There have been some claims for VHE gamma-ray emission from the Vela pulsar so far (Grindlay *et al.* 1975; Bhat *et al.* 1987). However, no positive evidence has been found in later observations (Bowden *et al.* 1993; Nel *et al.* 1993; Edwards *et al.* 1994). In these observations, period analyses were used to reduce cosmic-ray background counts and to search for pulsed gamma-ray emission. On the contrary, VHE emission from the Crab and PSR B1706 – 44 is apparently unpulsed. Therefore, it is important to look for the unpulsed VHE gamma-ray signal also from the Vela pulsar. For the Crab pulsar, intense X-ray emission is observed as an X-ray synchrotron nebula of which the inverse Compton counterpart is the source of VHE gamma rays. The energy injection, which is close to the spindown luminosity of the Crab pulsar (PSR B0531 + 21), is through a flow of relativistic electrons and positrons, i.e. a “pulsar wind” (Kennel & Coroniti 1984). The shock generated when the pulsar wind collides with circumstellar matter is likely to be the site of particle acceleration. It is likely that a similar process takes place at the Vela pulsar.

The Vela pulsar is relatively close to us, at a distance of about 500 pc, and we can expect to resolve the structure of the pulsar wind and nebula better than in the case of the

Crab (at a distance of ~ 2 kpc). In the X-ray energy band, a compact nebula was detected by the *Einstein* satellite with fainter extended emission (Harnden *et al.* 1985), which was later identified as an X-ray jet by the *ROSAT* satellite extending from the pulsar to the south-southwest direction and which Markwardt & Ögelman (1995) argued may be evidence of a pulsar wind from the Vela pulsar. The “head” of the Vela jet has been observed also by the *ASCA* satellite and the authors explored the possibility that the jet emission is non-thermal (synchrotron) radiation rather than thermal (Markwardt & Ögelman 1997). If the X-ray emission is of non-thermal origin, the detection of Compton-boosted VHE gamma rays would provide direct and clear evidence of non-thermal electrons.

2. Instruments and Observations

The 3.8 m telescope of the CANGAROO collaboration (Hara *et al.* 1993) detects Čerenkov photons from extensive air showers generated by primary gamma rays or cosmic rays, and has an imaging camera of 256 Hamamatsu R2248 square photomultiplier tubes. One photomultiplier tube views an angular extent of $0^\circ.12 \times 0^\circ.12$, and the total field of view of the camera is about 3° across.

The tracking accuracy of the telescope has been checked by monitoring the tracks of bright stars in the field of view. Monte Carlo simulations show the accuracy of calibrating the target position using star tracks to be better than $0^\circ.02$ (Yoshikoshi 1996). At least four bright stars of visual magnitude $5 \sim 6$ are in the 3° field of view around the Vela pulsar and the telescope pointing has been checked night by night.

The Vela pulsar has been observed by the 3.8 m telescope from January 1993 to March 1995. The on-source data amount to about 174 hours in total with a cosmic-ray event rate of about 1 Hz. Almost the same amount of off-source data has been taken, in paired

on-source and off-source runs each night. About 119 hours usable on-source data remain after rejecting the data affected by clouds. Only the data taken without cloud are used in the following analyses.

3. Analyses and Results

The Čerenkov imaging analysis is based on parameterization of the shape, location and orientation of approximately elliptical Čerenkov images detected by an imaging camera. The commonly used parameters are “width”, “length”, “conc” (shape), “distance” (location) and “alpha” (orientation) (Hillas 1985; Weekes *et al.* 1989; Reynolds *et al.* 1993) and the gamma-ray selection criteria in the present analysis are $0^{\circ}01 < \text{width} < 0^{\circ}09$, $0^{\circ}1 < \text{length} < 0^{\circ}4$, $0.3 < \text{conc}$, $0^{\circ}7 < \text{distance} < 1^{\circ}2$ and $\text{alpha} < 10^{\circ}$. Monte Carlo simulations show that more than 99 % of background events are rejected after the above selections are made, while ~ 50 % of gamma-ray images from a point source remain.

First, we searched for a gamma-ray signal from the pulsar position and found a significant excess of on-source events above the background (off-source) level. However, the peak profile of the excess distribution against the orientation angle “alpha” was broader than expected from a point source. Next, the assumed position of gamma-ray emission was shifted from the pulsar position, to scan a $2^{\circ} \times 2^{\circ}$ area around the pulsar within the field of view. The position of the maximum excess counts was searched for and found to be offset from the pulsar by about $0^{\circ}13$. Figure 1 shows the alpha distributions for the position of the maximum excess counts after the other selection criteria have been applied.

EDITOR: PLACE FIGURE 1 HERE.

The statistical significance of the excess after including the selection of alpha is at the 5.2σ level, where the statistical significance is calculated by $(N_{\text{on}} - N_{\text{off}})/\sqrt{N_{\text{on}} + N_{\text{off}}}$, and N_{on}

and N_{off} are the numbers of gamma-ray-like events in the on-source and off-source data, respectively.

In the usual image analysis, the image parameters are calculated from the mean and second moments of light yield, i.e. assuming gamma-ray images to have a simple elliptical shape. Gamma-ray images, however, are asymmetrical along their major axes, having an elongated, comet-like shape with the “tail” pointing away from the source position. This feature can be characterized and quantified by another image parameter called the “asymmetry”, which is the cube root of the third moment of the image along the major axis normalized by “length” (Punch 1993). Figure 2 (a) shows the asymmetry distributions for gamma-ray images for a point source and background (proton) images, inferred from Monte Carlo simulations.

EDITOR: PLACE FIGURE 2 HERE.

About 80 % of gamma-ray images have positive values of “asymmetry” in the simulation, while the distribution of background images is almost symmetrical because of their isotropic arrival directions. The asymmetry analysis has been applied assuming the source lies at the position of the maximum excess counts, to examine the gamma-ray-like feature of the excess events. The on-source distribution appears nearly symmetrical as shown in Figure 2 (b). However, after subtracting the off-source distribution, the distribution of the excess events in Figure 2 (c) is asymmetrical with the peak on the positive side as expected from the simulation. This result gives clear corroborative evidence that the detected excess events of Figure 1 are truly due to gamma rays. The significance of 5.2σ for the excess counts in the alpha distribution of Figure 1 increases to 5.8σ by adding asymmetry > 0 to the gamma-ray selection criteria.

As an alternative method to calculating the alpha parameter, it is possible to infer and

assign the true direction of a gamma ray from the location and orientation of its observed Čerenkov image. We have calculated a probability density for the true direction for each observed gamma-ray image using Monte Carlo simulations (Yoshikoshi 1996). Thus, a density map of gamma-ray directions can be obtained by adding up all of the probability densities of the gamma-ray-like images. The contribution of the gamma-ray source in the field of view can then be found as an event excess in the on-source map over the background (off-source) map. Figure 3 shows the density map of the excess events for the Vela pulsar data plotted as a function of right ascension and declination.

EDITOR: PLACE FIGURE 3 HERE.

The significant excess due to a gamma-ray source near the pulsar exists in this map. The position of maximum emission is offset from the pulsar, which is indicated by the “star” mark in the map, to a position southeast by about $0^{\circ}13$. The alpha distribution of Figure 1 is plotted for the position of maximum emission.

The gamma-ray integral flux calculated for the position of the maximum excess counts is $(2.9 \pm 0.5 \pm 0.4) \times 10^{-12}$ photons $\text{cm}^{-2} \text{sec}^{-1}$ above 2.5 TeV, where the first and second errors are statistical and systematic respectively. The flux from the pulsar position is 1.4×10^{-12} photons $\text{cm}^{-2} \text{sec}^{-1}$ above 2.5 TeV. However, the excess counts which are calculated for the positions of the maximum excess counts and the pulsar are not independent of each other and all of the flux measured from the pulsar position is possibly contamination by the events from the position of the maximum excess counts. The threshold energy is defined as the energy of the maximum differential flux of detected gamma-ray-like events and has been estimated from Monte Carlo simulations to be 2.5 TeV, assuming a power law spectrum with a photon index of -2.5 . The systematic error for this threshold energy is about ± 1.0 TeV, which is due to uncertainties in the photon index, the trigger conditions and the reflectivity of the mirror. The data have been divided to

calculate year-by-year fluxes and the fluxes are consistent with no variation having been detected on the time scale of two years.

The periodicity of the events detected from the Vela pulsar direction and the direction of the maximum excess counts has been investigated using our 1994 and 1995 data for which a global positioning system (GPS) was available. A derivative of the TEMPO programs (Taylor & Weisberg 1989) has been used to transform the event arrival times to solar system barycentric (SSB) arrival times. The solar system ephemeris used in the analysis comes from the Jet Propulsion Laboratory (JPL) and is based on epoch 2000 (DE 200) (Standish 1982). We have applied the Z_2^2 test (Buccheri *et al.* 1983) to the data set after the gamma-ray selection with the period of the Vela pulsar using ephemerides from the Princeton data base (Arzoumanian *et al.* 1992), and the test has been done coherently for each year. No significant value of the Z_2^2 statistic has been found for either the excess direction nor the pulsar direction. The 95 % confidence upper limit to the pulsed flux has been calculated for the pulsar position as $(3.7 \pm 0.7) \times 10^{-13}$ photons $\text{cm}^{-2} \text{sec}^{-1}$ above 2.5 TeV from the values of Z_2^2 using the method of Protheroe (1987).

4. Discussion

The luminosity of VHE gamma rays from the position of the maximum excess counts near the Vela pulsar is calculated to be $\sim 6.0 \times 10^{32}$ erg sec^{-1} , assuming that the distance to the gamma-ray emission region is 500 pc, the photon index of the power law spectrum is -2.5 , the maximum gamma-ray energy is 10 TeV and the emission is isotropic. The VHE luminosity corresponds to $\sim 8.6 \times 10^{-5}$ of the pulsar's spindown energy of 6.9×10^{36} erg sec^{-1} , and is smaller by an order of magnitude than the luminosity of pulsed emission in the range from 100 MeV to 2 GeV (Kanbach *et al.* 1994). The luminosity of VHE gamma rays from the pulsar position is estimated to be $\sim 2.9 \times 10^{32}$ erg sec^{-1} , which

should rather be interpreted as an upper limit because a majority of the excess events at the pulsar position are common with the events of the maximum excess position.

The emission region of VHE gamma rays appears to differ by about $0^{\circ}.13$ to the southeast from the Vela pulsar position. We have investigated whether the effect of statistical fluctuations could cause a change in the observed source position, using Monte Carlo simulations. The position error derived for a point source of this strength is estimated to be about $0^{\circ}.04$, and so the observed offset of the detected peak position from the pulsar corresponds to a significance of more than 3σ . In this estimation, we ignored the effect due to the source extent and, in fact, the peak profile which appears in Figure 3 seems to be rather more extended than the point spread function (HWHM $\sim 0^{\circ}.18$). We note also that separate maps of each year’s data show consistent offsets. The 3.8 m mirror has recently been recoated and the Vela pulsar region has been observed with a better reflectivity ($\sim 90\%$) again in 1997 further to confirm the offset. We have found a gamma-ray-like event excess from the 1997 data with a significance of more than 4σ and the position of maximum excess counts, indicated by the “cross” in Figure 3, agrees with that from the 1993 to 1995 data within the statistical error.

The southeast offset of $0^{\circ}.13$ corresponds to about 1 pc for the distance of 500 pc, much larger than the size of the light cylinder, and thus, we can exclude the possibility that the detected signal is from the pulsar magnetosphere or from the X-ray jet. This conclusion is consistent with there being no pulsation detected at the pulsar period. Unpulsed VHE emission at a distance of ~ 1 pc from the pulsar may suggest that the mechanism for generating relativistic particles and inverse Compton gamma rays in the Vela pulsar and nebula is similar to the case of the Crab pulsar and nebula. A shock due to the confinement of the pulsar wind by the nebula may exist or have formed at the position southeast of the Vela pulsar by about $0^{\circ}.13$. This position of the VHE emission agrees with the birthplace

of the Vela pulsar (Ögelman *et al.* 1989; Bailes *et al.* 1989). Accelerated electrons could survive longer than the pulsar age if the magnetic field is not strong, and the VHE emission may be due to such long-lived electrons as pointed out by Harding & de Jager (1997). Recent X-ray observations show that a number of young pulsars are accompanied by possible synchrotron nebulae (Kawai & Tamura 1996), which are offset from the pulsars. The existence of relativistic electrons in a region displaced from the pulsar may be rather a common feature observed in pulsar/nebula systems. VHE gamma rays could well be produced by electrons in such displaced regions as we observe in the case of the Vela pulsar and nebula.

In the *ROSAT* X-ray image (Markwardt & Ögelman 1995), a “bright spot” can be found where we have detected the VHE gamma-ray signal. Assuming that the X-rays originate in synchrotron emission from the same electrons that, through inverse Compton scattering, produce the VHE gamma rays, we can estimate the magnetic field from the relation $L_{\text{syn}}/L_{\text{iC}} = U_B/U_{\text{ph}}$ of inverse Compton luminosity L_{iC} and synchrotron luminosity L_{syn} , where $U_B = B^2/8\pi$ and U_{ph} are the energy densities of the magnetic field and the photon field, respectively. The X-ray luminosity from the bright spot at the pulsar birthplace is estimated from the *ROSAT* image to be smaller than that from the 1' X-ray nebula around the pulsar, 1.3×10^{33} erg sec⁻¹ per decade of energy (Ögelman *et al.* 1993), while the VHE gamma-ray luminosity is $\sim 1.0 \times 10^{33}$ erg sec⁻¹ per decade. An upper limit for the magnetic field at the bright spot is then estimated to be $B \lesssim 4 \times 10^{-6} (U_{\text{ph}}/0.24 \text{ eV cm}^{-3})^{1/2}$ G, where 0.24 eV cm⁻³ is the energy density of the microwave background photons. As for the compact X-ray nebula, a lower limit for the magnetic field can be estimated from the upper limit for the VHE gamma-ray luminosity from the pulsar position, i.e. $B \gtrsim 5 \times 10^{-6} (U_{\text{ph}}/0.24 \text{ eV cm}^{-3})^{1/2}$ G. This limit is compatible with an estimate obtained by de Jager *et al.* (1996) from a confinement condition for the progenitor electrons. A plausible scenario is thus that the VHE gamma-ray emission occurs

from the X-ray bright spot offset $0^{\circ}13$ from the pulsar to the southeast where there is sufficient density of relativistic electrons, but a smaller magnetic field.

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Fig. 1.— Distributions of the image orientation angle “alpha” with respect to the direction of the maximum excess counts, which is offset by about $0^{\circ}13$ to the southeast from the Vela pulsar and corresponds to the peak position in Figure 3: (a) on-source (solid line) and off-source (dashed line) distributions; (b) distribution of the excess counts of the on-source above the background (off-source) level. For gamma-ray-like events, one expects this angle to be close to zero.

Fig. 2.— Distributions of the “asymmetry” parameter for simulated and observed Čerenkov images: (a) distributions of gamma-ray images for a point source (solid line) and background (proton) images (dashed line) inferred from Monte Carlo simulations; (b) on-source (solid line) and off-source (dashed line) distributions of gamma-ray-like events for the direction of the maximum excess counts, which is the same as in Figure 1; (c) distribution of the excess counts of the on-source above the background. This parameter measures the pointing of the images toward the source, as indicated by positive values.

Fig. 3.— A density map of excess counts around the Vela pulsar plotted as a function of right ascension and declination; north is up and east is to the left. The gray scale at the right is in counts degree⁻². The “star” at the origin of the map indicates the position of the Vela pulsar. We have observed the same field of view also in 1997 with a reduced energy threshold, to confirm the offset of the source from the pulsar. The position of the maximum excess counts from the 1997 data is indicated by the “cross” in the map.





