VERY HIGH ENERGY GAMMA RAYS FROM THE VELA PULSAR DIRECTION

T. YOSHIKOSHI,1, 2 T. KIFUNE,2 S. A. DAZELEY,3 P. G. EDWARDS,3, 4 T. HARA,5 Y. HAYAMI,1 F. KAKIMOTO,1 T. KONISHI,6 A. MASAIKE,7 Y. MATSUBARA,8 T. MATSUOKA,8 Y. MEZUMOTO,9 M. MORI,10 H. MURAISHI,11 Y. MURAKI,8 T. NAITO,12 K. NISHIJIMA,13 S. ODA,6 S. OGIO,1 T. OHSAKI,1 J. R. PATTERSON,3 M. D. ROBERTS,2 G. P. ROWELL,3 T. SAKO,9 K. SAKURAZAWA,1 R. SUSUKITA,7, 14 A. SUZUKI,6 T. TAMURA,15 T. TANIMORI,1 G. J. THORNTON,2, 3 S. YANAGITA,11 AND T. YOSHIDA11

Y. MATSUBARA,8 T. MATSUOKA,8 Y. MIZUMOTO,9 M. MORI,10 H. MURAISHI,11 Y. MURAKI,8 T. NAITO,12 K. NISHIJIMA,13 S. ODA,6 S. OGIO,1 T. OHSAKI,1 J. R. PATTERSON,3 M. D. ROBERTS,2 G. P. ROWELL,3 T. SAKO,9 K. SAKURAZAWA,1 R. SUSUKITA,7, 14 A. SUZUKI,6 T. TAMURA,15 T. TANIMORI,1 G. J. THORNTON,2, 3 S. YANAGITA,11 AND T. YOSHIDA11

Received 1997 May 16; accepted 1997 July 3

ABSTRACT

We have observed the Vela pulsar region at TeV energies using the 3.8 m imaging Čerenkov telescope near Woomera, South Australia between 1993 January and 1995 March. Evidence of an unpulsed gamma-ray signal has been detected at the 5.8 σ level. The detected gamma-ray flux is $(2.9 \pm 0.5 \pm 0.4) \times 10^{-12}$ photons cm$^{-2}$ s$^{-1}$ above 2.5 ± 1.0 TeV, and the signal is consistent with steady emission over the 2 years. The gamma-ray emission region is offset from the Vela pulsar position by about $0.0 \pm 0.1$. 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 cm$^{-2}$ s$^{-1}$ above 2.5 ± 1.0 TeV.

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

1. INTRODUCTION

It is highly likely that high-energy particles are accelerated by nonthermal 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 and 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 that VHE gamma rays initiate in the upper atmosphere. The Vela pulsar, PSR B0833−24, 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. In contrast, 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 spin-down 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 nonthermal (synchrotron) radiation rather than thermal (Markwardt & Ögelman 1997). If the X-ray emission is of nonthermal origin, then the detection of Compton-boosted VHE gamma rays would provide direct and clear evidence of nonthermal 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 0.12 × 0.12, 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 0.02̅ (Yoshikoshi 1996). At least four bright stars of visual magnitude 5–6 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 1993 January to 1995 March. The on-source data amount to about 174 hr 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 hr usable on-source data remain after rejecting the data affected by clouds. Only the data taken without clouds 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,” “cone” (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 $0.01 < \text{width} < 0.09$, $0.1 < \text{length} < 0.4$, $0.3 < \text{conc}$, $0.7 < \text{distance} < 1.2$, and $\alpha < 10^\circ$. Monte Carlo simulations show that more than 99% of background events are rejected after the above selections are made, while about 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 off-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° area around the Vela pulsar, and the telescope pointing has been checked night by night.

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 Cˇerenkov 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 2a shows the asymmetry distributions for gamma-ray images for a point source and background (proton) images, inferred from Monte Carlo simulations. 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 that 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...
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 $\pm 1.0$ 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 timescale of 2 yr.

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 $Z^2_1$ 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 database (Arzoumanian et al. 1992), and the test has been done coherently for each year. No significant value of the $Z^2_1$ statistic has been found for either the excess direction or the pulsar direction. The 95% confidence upper limit to the pulsed flux has been calculated for the pulsar position as $(3.7 \pm 0.7) \times 10^{-11}$ photons cm$^{-2}$ s$^{-1}$ above 2.5 TeV from the values of $Z^2_1$ 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 about $6.0 \times 10^{32}$ ergs s$^{-1}$, 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 about $8.6 \times 10^{35}$ of the pulsar’s spin-down energy of $6.9 \times 10^{36}$ ergs s$^{-1}$ 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 about $2.9 \times 10^{32}$ ergs s$^{-1}$, 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 $0.13$ 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 $0.04$, and so the observed offset of the detected peak position from the pulsar corresponds to a significance of more than $3 \sigma$. In this estimation, we ignored the effect due to the source extent, and, in fact, the peak profile that appears in Figure 3 seems to be rather more extended than the point-spread function (HWHM $\sim 0.18$). 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

nearly symmetrical, as shown in Figure 2b. However, after subtracting the off-source distribution, the distribution of the excess events in Figure 2c 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 5.2 $\sigma$ for the excess counts in the alpha distribution of Figure 1 increases to 5.8 $\sigma$ 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 Cherenkov 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. 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 $0.13$. 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 cm$^{-2}$ s$^{-1}$ above 2.5 TeV, where the first and second errors are statistical and systematic, respectively. The flux from the pulsar position is $1.4 \times 10^{-12}$ photons cm$^{-2}$ s$^{-1}$ above 2.5 TeV. However, the excess counts that 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

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 deg$^{-2}$. 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.
observed with a better reflectivity (~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 4 σ, 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°13 corresponds to about 1 pc for the distance of 500 pc, much larger than the size of the light cylinder; 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 about 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°13. This position of the VHE emission agrees with the birthplace of the Vela pulsar (Ögelman, Koch-Miramond, & Aurie`re 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 $L_{\gamma} = U_{\gamma}/\phi_{\gamma}$ of inverse Compton luminosity $L_{\gamma}$ and synchrotron luminosity $L_{\gamma}$, where $U_{\gamma} = B^2/8\pi$ and $\phi_{\gamma}$ 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} ergs s^{-1} per decade of energy (Ögelman, Finley, & Zimmermann 1993), while the VHE gamma-ray luminosity is about 1.0 × 10^{33} ergs s^{-1} per decade. An upper limit for the magnetic field at the bright spot is then estimated to be $B \approx 4 \times 10^{-4} (U_{\gamma}/0.24 \text{ eV cm}^{-3})^{1/2}$ 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., $B \approx 5 \times 10^{-5} (U_{\gamma}/0.24 \text{ eV cm}^{-3})^{1/2}$ G. This limit is compatible with an estimate obtained by de Jager, Harding, & Strickman (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°13 from the pulsar to the southeast where there is sufficient density of relativistic electrons but a smaller magnetic field.

This work is supported by International Scientific Research Program of a Grant-in-Aid in Scientific Research of the Ministry of Education, Science, Sports, and Culture, Japan, and by the Australian Research Council, T. Kifune and T. Tanimori acknowledge the support of the Sumitomo Foundation. The receipt of JSPS Research Fellowships (P. G. E., T. N., M. D. R., K. S., G. J. T., and T. Yoshikoshi) is also acknowledged.

REFERENCES

Arzoumanian, Z., Nice, D., & Taylor, J. H. 1992, GRO/Radio Timing Database (Princeton: Princeton Univ.)

Bailes, M., et al. 1989, ApJ, 343, L53

Bhat, P. N., et al. 1987, A&A, 178, 242

Bowden, C. C. G., et al. 1993, Proc. 23d Int. Cosmic-Ray Conf. (Calgary), 1, 294

Buccheri, R., et al. 1983, A&A, 128, 245

Buecheri, R., et al. 1983, A&A, 128, 245

de Jager, O. C., Harding, A. K., & Strickman, M. S. 1996, ApJ, 460, 729

Edwards, P. G., et al. 1994, A&A, 291, 468

Grindlay, J., et al. 1975, ApJ, 201, 82

Hara, T., et al. 1993, Nucl. Instrum. Methods Phys. Res. A, 332, 300

Harding, A. K., & de Jager, O. C. 1997, in Proc. 32d Rencontres de Moriond, Extragalactic Astronomy in the Infrared, ed. G. A. Mamon, T. X. Thuan, & J. T. T. Ván (Editions Frontieres: Gif-sur-Yvette), in press

Harnden, F. R., et al. 1985, ApJ, 299, 828

Hillas, A. M. 1985, Proc. 19th Int. Cosmic-Ray Conf. (La Jolla), 3, 445

Kanbach, G., et al. 1994, A&A, 289, 855

Kawai, N., & Tamura, K. 1996, Proc. IAU Colloq. 160, Pulsars: Problems and Progress, ed. S. Johnston, M. A. Walker, & M. Bailes (San Francisco: ASP), 367

Kennel, C. F., & Coroniti, F. V. 1984, ApJ, 283, 694

Kifune, T. 1996, Proc. IAU Colloq. 160, Pulsars: Problems and Progress, ed. S. Johnston, M. A. Walker, & M. Bailes (San Francisco: ASP), 359

Kifune, T., et al. 1995, ApJ, 438, L91

Markwardt, C. B., & Ögelman, H. 1995, Nature, 375, 40

—. 1997, ApJ, 480, L13

Nel, H. I., et al. 1993, ApJ, 418, 836

Ögelman, H., Finley, J. P., & Zimmermann, H. U. 1993, Nature, 361, 136

Ögelman, H., Koch-Miramond, L., & Aurie`re, M. 1989, ApJ, 342, L83

Protheroe, R. J. 1987, Proc. Astron. Soc. Australia, 7(2), 167

Punch, M. 1993, Ph.D. thesis, National Univ. Ireland

Ramanamurthy, P. V., et al. 1995, ApJ, 447, L109

Reynolds, P. T., et al. 1993, ApJ, 404, 206

Standish, E. M. 1982, A&A, 114, 297

Tanimori, T., et al. 1994, ApJ, 429, L61

Taylor, J. H., & Weisberg, J. M. 1989, ApJ, 345, 434

Vacanti, G., et al. 1991, ApJ, 377, 467

Weckes, T. C., et al. 1989, ApJ, 342, 379

Yoshikoshi, T. 1996, Ph.D. thesis, Tokyo Inst. Technol.