VERY HIGH ENERGY GAMMA-RAY OBSERVATIONS OF PSR B1509−58 WITH THE CANGAROO 3.8 METER TELESCOPE

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ABSTRACT

The gamma-ray pulsar PSR B1509−58 and its surrounding nebulae have been observed with the collaboration of Australia and Nippon for a Gamma-Ray Observatory in the Outback (CANGAROO) 3.8 m imaging atmospheric Cerenkov telescope. The observations were performed from 1996 to 1998 in Woomera, South Australia, under different instrumental conditions with estimated threshold energies of 4.5 (1996), 1.9 (1997), and 2.5 TeV (1998) at zenith angles of ~30°. Although no strong evidence of gamma-ray emission was found, the lowest energy threshold data of 1997 showed a marginal excess of gamma-ray–like events at the 4.1 σ significance level. The corresponding gamma-ray flux is calculated to be (2.9 ± 0.7) × 10^{-12} cm^{-2} s^{-1} above 1.9 TeV. The observations of 1996 and 1998 yielded only upper limits (99.5% confidence level) of 1.9 × 10^{-12} cm^{-2} s^{-1} above 4.5 TeV and 2.0 × 10^{-12} cm^{-2} s^{-1} above 2.5 TeV. Assuming that the 1997 excess is due to very high energy (VHE) gamma-ray emission from the pulsar nebula, our result, when combined with the X-ray observations, leads to a value of the magnetic field strength ~5 μG. This is consistent with the equipartition value previously estimated in the X-ray nebula surrounding the pulsar. No significant periodicity at the 150 ms pulsar period has been found in any of the three years’ data. The flux upper limits set from our observations are 1 order of magnitude below previously reported detections of pulsed TeV emission.

Subject headings: gamma rays: observations — pulsars: individual (PSR B1509−58) — supernova remnants

1. INTRODUCTION

Pulsar nebulae have been suggested as possible acceleration sites for high-energy particles in our Galaxy (Harding 1990). The first-order Fermi acceleration mechanism is expected to occur in a shock between the pulsar wind and supernova ejecta or interstellar matter. Evidence of such energetic phenomena has been obtained through observation of synchrotron emission by accelerated electrons and positrons at radio to gamma-ray (≤10 GeV) energies. However, more direct evidence has become obtainable through very high energy (VHE) gamma-ray (≥300 GeV) observations over the last decade using the imaging atmospheric Cerenkov technique (IACT).

VHE gamma-ray emissions from the directions of three energetic pulsars, the Crab pulsar (Weeke et al. 1989; Vacanti et al. 1991; Tanimori et al. 1994), the Vela pulsar (Yoshikoshi et al. 1997), and PSR B1706−44 (Kifune et al. 1995; Chadwick et al. 1997), have been detected by ground-based telescopes using the IACT. Although all three pulsars show pulsed emission in the EGRET energy range (100 MeV–10 GeV), none of the VHE gamma-ray detections have shown any periodicity at the radio pulsar period. This steady VHE gamma-ray emission is usually explained as being a result of the inverse Compton scattering in the pulsar nebula and not from the pulsar magnetosphere. While the mechanism of the emission from the Crab nebula is well studied (see, for example, de Jager et al. 1996), information on other pulsars is still sparse. In order to study pulsars and their surrounding environment as possible acceleration sites for cosmic rays, more examples in the VHE gamma-ray range are required.

PSR B1509−58 was discovered as an X-ray pulsar by Seward & Harnden (1982) using the Einstein X-Ray Observatory. It is near the center of the supernova remnant MSH 15−52 (G320.4−1.2). Soon after this discovery, pulsed radio emission was found by Manchester, Tuohey, & D’Amico (1982). The pulsar has a period of 150 ms and a period derivative of 1.5 × 10^{-12} s^{-1}, the largest known
today. The characteristic age of the pulsar is estimated to be ~1700 yr (Manchester et al. 1998), which makes it the second youngest pulsar after the Crab.16 From the period and the large period derivative, a very strong surface magnetic field of $1.5 \times 10^{12}$ G and a large spin-down energy loss rate of $1.8 \times 10^{37}$ ergs s$^{-1}$ are implied. While the distance to the pulsar is relatively large (4.4 kpc; Taylor et al. 1995), the expected energy flux received at the Earth is the fifth largest among the known pulsars.

A compact ($\sim 10' \times 6'$) synchrotron X-ray nebula has been found to exist around PSR B1509$-$58 (Seward et al. 1984). The synchrotron emission suggests the existence of nonthermal electrons (positrons) in the nebula, which would also emit VHE gamma rays via inverse Compton scattering. A detectable VHE gamma-ray flux from this synchrotron nebula was predicted by du Plessis et al. (1995) as a function of the magnetic field strength in the nebula. The expected gamma-ray flux above 1 TeV of $10^{-11}$ to $10^{-12}$ cm$^{-2}$ s$^{-1}$ for nebula magnetic fields 4$-$10 $\mu$G is within the sensitivity of the Collaboration of Australia and Nippon for a Gamma-Ray Observatory in the Outback (CANGAROO) 3.8 m telescope. Thus, VHE observations should give a good measurement of the magnetic field strength of this nebula. Du Plessis et al. (1995) also predicted a very hard differential spectral index of $\sim 1.8$ based on the X-ray observations. This prediction provides us with an extreme example of the utility of multiwavelength studies of synchrotron inverse Compton-emitting objects. Besides the compact nebula, recent X-ray satellite observations suggest various nonthermal phenomena in this remnant. ROSAT observations indicate a nonthermal X-ray component from the central diffuse nebula (CDN) extending to a diameter of 50' ($\sim 60$ pc centered on the pulsar; Trussoni et al. 1996). ASCA observations revealed a nonthermal jet structure between the pulsar and the center of a thermal nebula about 10' north from the pulsar (Tamura et al. 1996). In order to explain the effective thermalization process of the thermal nebula, Tamura et al. (1996) indicate the existence of accelerated ions as well as electrons in the jet. Furthermore, Gaensler et al. (1999) found synchrotron emission from compact knots in this thermal nebula from 20 cm imaging observations with the Australia Telescope Compact Array.

The surface magnetic field strength of the pulsar PSR B1509$-$58 is estimated to be one of the largest among known pulsars. Because of the photon splitting process caused by this strong surface magnetic field, a cutoff in the pulsed emission around MeV energies was predicted by Harding, Baring, & Gonthier (1997). In fact, Kuiper et al. (1999) have suggested that a cutoff around 10 MeV exists in the Compton Telescope (COMPTEL) data. EGRET observations have resulted in only an upper limit for the pulsed emission from PSR B1509$-$58 (Thompson et al. 1994). In contrast, Nel et al. (1992) have reported the detection of transient pulsed VHE gamma rays from the observations between 1985 and 1988 based on ground-based (nonimaging) Cerenkov telescope observations. However, they could not detect any significant pulsed emission in the successive years. They tried to explain their observations within the framework of the outer gap model (Cheng, Ho, & Ruderman 1986). Bowden et al. (1993) reported an upper limit of the pulsed emission above 0.35 TeV from their observations in 1987 and 1989. Combining with the detection by Nel et al. (1992) in 1987 above 1.5 TeV, the power-law index of the integral energy spectrum is limited to being harder than $\sim 1$. Interestingly, Kuiper et al. (1999) also indicate a marginal detection of pulsed emission above 10 MeV, where the origin may differ from that at lower energies. Consequently, we have examined our data for the presence of periodicity as well. Our observations are the first results on this pulsar using data from the IACT, which is 1 order of magnitude more sensitive than nonimaging observations.

For the reasons given above, we believed that PSR B1509$-$58 would be an interesting object to study above 1 TeV energies with the CANGAROO 3.8 m IACT telescope in both the steady nebula emission and the pulsed emission. Details of those observations are given in § 2. The methods of the analysis and results are shown in § 3. In § 4, we summarize our results and discuss their implications.

2. OBSERVATIONS

The CANGAROO 3.8 m telescope is located at Woomera, South Australia (136°47'E, 31°6'S, and 160 m above sea level). Cerenkov photons emitted from extensive air showers originated by primary gamma rays and cosmic rays are collected with a parabolic mirror of 3.8 m diameter and detected with an imaging camera at the focal plane. The camera consists of 256 photomultiplier tubes (PMTs) of 10 $\times$ 10 mm size (Hamamatsu R2248). The PMTs are located in a 16 $\times$ 16 square grid, and the field of view amounts to 3° $\times$ 3°. When signals from more than five tubes exceed 5 photoelectrons each within a gate, a trigger is generated. The amplitude and relative time of each PMT signal, the event time, and the counting rate of each tube are recorded for each event. The absolute time can be obtained with a precision of $\pm$ 200 ns using a global positioning system (GPS) clock. In addition to the GPS clock, the time of a crystal clock with a precision of $\pm$ 100 $\mu$s is also recorded. The GPS clock was not available in the 1997 observations because of the installation work on our new data acquisition system. However, because the time indicated by the crystal clock shows a stable drift from that of the GPS clock, we can obtain accurate relative arrival times for events even without the GPS clock. The crystal clock is reset every observation (new-month) period. Therefore, a periodicity analysis based on this clock is valid on a month by month basis. GPS timing was restored in July 1997. Details of the camera and the telescope are described in Hara et al. (1993).

The telescope was pointed in the direction of the pulsar PSR B1509$-$58 (right ascension 15°13'55''.62 and declination $-59'08'08.9''$ [J2000]; Taylor et al. 1995) in 1996 May and June, from 1997 March to May, and from 1998 March to May. The pulsar (on source) and an offset region (off source) with the same declination as the pulsar but different right ascension were observed for equal amounts of time each night under moonless and usually clear sky conditions. Typically, the on-source region was observed only once in a night around transit for a few hours. Two off-source runs were carried out before and after the on-source run. The former one covered the first one-half of the on-source track, and the latter covered the second one-half. In the off-line analysis, those data obtained when a small

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16 Torii et al. (1997) have reported the discovery of a pulsar 1600 years old. This age is somewhat speculative, however, as the period derivative of the pulsar has not yet been measured and an association with a historical supernova was assumed to estimate the pulsar age.
patch of cloud was obscuring the source were omitted. At the same time, the corresponding on (or off) source data were also rejected from the analysis. In addition to the weather selection, the data taken when the electronics noise produced an anomalously large trigger rate were not used in the analysis. This happened in the 1996 observations. In the 1998 data, there are many nights that have a large difference in the event rate between the on and off-source regions, which is thought to be due to the presence of thin dew on the reflecting mirror. Data taken under these conditions were also omitted. The durations of selected observations after these procedures are 26 hr 30 minutes, 32 hr 8 minutes, and 21 hr 14 minutes for the 1996, 1997, and 1998 (both on and off) data, respectively. These data are used for the analysis in this paper.

Observations were carried out under different instrumental conditions in each year. During the 1996 observations, the reflectivity of the mirror was estimated to be \( \approx 45\% \). We recoated the mirror in October 1996 by vacuum evaporation of aluminum at the Anglo-Australian Observatory. As a result, the reflectivity of the mirror increased to about 90%. As the reflectivity was improved, the threshold energy of our telescope was lowered. For the 1997 observations, the threshold energy, defined here as the energy at which a differential photon flux with an assumed differential spectral index of 2.5 is maximized in the Monte Carlo calculations, was estimated to be 1.9 TeV, compared with 4.5 TeV before the recoating. By the 1998 observations, the reflectivity had decreased to \( \approx 70\% \), corresponding to a threshold energy of 2.5 TeV. In these estimations, the selection effect of the analysis described in the next section is also taken into account. In the Monte Carlo calculation, we assumed that the observations were made at a zenith angle of 30\(^\circ\), which was close to the average value for our observations on PSR B1509 \(-\) 58.

The observation times and threshold energies are summarized in Table 1, and the analysis results are shown as well.

### 3. ANALYSIS AND RESULTS

#### 3.1. Analysis Method

At the beginning of each run, the analog-to-digital converter (ADC) pedestal and gain for each PMT were measured. To calibrate the gain, a blue LED located at the center of the mirror was used to illuminate the PMTs uniformly. The pedestal value was subtracted from the ADC value, and any variations in the PMT gains were normalized using the LED calibration data. PMTs whose time-to-digital converter (TDC) value corresponded to a pulse arrival time within \( \pm 30 \) ns of the shower plane were regarded as “hit” tubes and used to calculate image parameters. After omitting some hit tubes that were isolated or that had ADC values less than 1 standard deviation above the pedestal value, the conventional image parameters (Hillas 1985) were calculated. (In the 1996 data, one-fifth of the PMTs at the bottom in the camera were omitted from analysis to avoid the effect of electronics noise. This makes the threshold energy higher and the effective area smaller. This effect is included in calculating the threshold energy and the flux upper limit.)

The parameter ranges determined from Monte Carlo simulations to optimize the gamma-ray signals are 0\(^\circ\) 60\(^\circ\) distance \( \leq 1\) 30\(^\circ\), 0\(^\circ\) 04 \( < \) width \( \leq 0\) 09\(^\circ\), 0\(^\circ\) 10 \( < \) length \( \leq 0\) 40\(^\circ\), 0\(^\circ\) 35 \( < \) concentration \( \leq 0\) 70\(^\circ\), and \( \alpha \approx 10\(^\circ\). These ranges are slightly narrower than those used in the case of the Vela analysis (Yoshikoshi et al. 1997). The upper limit of \( \alpha \approx 10\(^\circ\), is adopted assuming the source is pointlike. Two orientation parameters, \( \alpha \) and distance, are defined with respect to the assumed source position in the field of view. In this paper, this is fixed at the pulsar position except in the spatial analysis discussed in § 3.4. To avoid the effect of incomplete images near the edge of the camera, images with centroids located at greater than 1\(^\circ\) 05 from the center of the camera were also rejected. We also required that the number of hit tubes \( (N_{hit}) \) must be \( \geq 5 \) and the total number of photoelectrons contained in an image \( (N_{pe}) \) must be \( \geq 40 \) to be able to obtain good image parameters and select only air shower–induced events. The upper limit of \( N_{pe} \) is large enough to accept all real events with large numbers of photoelectrons. In Table 1, the numbers of events in the raw data and those selected are presented. We can find a large difference between on source and off source in the raw data. The main reasons for the difference in number are the electronics noise in the 1996 data and the existence of the optically bright stars \( (M_v = 4.1 \) and 4.5) in the field of view in the 1997 data, where the reflectivity of the mirror was the largest. However, the numbers match well after the selected

| Observation Period | Time (min) | Threshold Energy (TeV) | Number of Events | Flux \( \times 10^{-12} \) cm \(^{-2}\) s \(^{-1}\) |
|--------------------|------------|------------------------|------------------|-------------------------------|
| 1996 on ............. | 1590       | 4.5                    | 91622            | 16111                         | 170       | <1.9                             |
| 1996 off ............ | 1590       | ...                    | 99948            | 17297                         | 169       | ...                              |
| 1997 on ............. | 1928       | 1.9                    | 367689           | 106624                        | 1388      | 2.9                              |
| 1997 off ............ | 1928       | ...                    | 282156           | 106772                        | 1180      | ...                              |
| 1998 on ............. | 1274       | 2.5                    | 89752            | 26543                         | 345       | <2.0                             |
| 1998 off ............ | 1274       | ...                    | 90002            | 26705                         | 309       | ...                              |
| 1997 Mar on ........  | 345        | ...                    | 73742            | 19440                         | 261       | 0.10 \( \pm \) 0.06               |
| 1997 Mar off ........ | 345        | ...                    | 62193            | 19610                         | 227       | ...                              |
| 1997 Apr on .......... | 598        | ...                    | 101909           | 33504                         | 426       | 0.12 \( \pm \) 0.05               |
| 1997 Apr off ..........| 598        | ...                    | 82334            | 33610                         | 381       | ...                              |
| 1997 May on .......... | 985        | ...                    | 192038           | 53680                         | 701       | 0.13 \( \pm \) 0.04               |
| 1997 May off ..........| 985        | ...                    | 137629           | 53552                         | 572       | ...                              |

Note.—The number of events in the after noise reduction column indicates those remaining after the \( N_{hit} \) and \( N_{pe} \) cuts are applied to obtain the number of air shower events. Flux upper limits for the 1996 and 1998 data are calculated as a 99.5% confidence level. For the 1997 data, the results in each new-moon season are also presented with the excess counts per minute.
of air shower events. For all three years’ data analyses we applied the same criteria as described above.

3.2. Results of the Image Analysis

The distributions of the orientation angle ($\alpha$) after all other cuts were applied are shown in Figure 1.

Although there was no statistically significant excess of the on-source counts over the off-source counts seen in the 1996 data, the 1997 data shows an excess at $\alpha \leq 10^\circ$ with a statistical significance of 4.1 $\sigma$. This excess may indicate the presence of a VHE gamma-ray signal from the source. The additional use of the asymmetry parameter showed an excess in the positive (gamma-ray–like) domain though not at a level that would have increased the overall significance of the excess. More careful study would be necessary in the use of this third-moment parameter for the source near the Galactic center, where the night-sky background level is high. In the 1998 data, we find a small excess in the on-source counts; however, the statistical significance is only 1.4 $\sigma$ at $\alpha \leq 10^\circ$. Hereafter, we regard the 1996 and 1998 results as nondetections of the VHE gamma-ray signal and treat the 1997 result as a marginal detection. The corresponding upper limits and flux are calculated as

$$F_{99.5\%}(E \geq 4.5 \text{ TeV}) \leq 1.9 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1},$$

$$F(E \geq 1.9 \text{ TeV}) = (2.9 \pm 0.7) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1},$$

and

$$F_{99.5\%}(E \geq 2.5 \text{ TeV}) \leq 2.0 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$$

for the 1996, 1997, and 1998 results, respectively. Here, a differential energy spectral index of 2.5 is assumed. The upper limits and the errors in the flux are estimated based on the numbers of the observed counts. We note that in our calculation of the upper limits the difference of the counts between on source and off source are also taken into account following the formula introduced by Helene (1983). Thus, the 1998 flux upper limit becomes higher than that from a completely null result. If we change the assumption of the differential energy spectral index over the range $2.5 \pm 1.0$, the corresponding threshold energies are estimated to change by $\sim \pm 30\%$. Instrumental uncertainties also affect the estimation of the threshold energies. We esti-

![Fig. 1.—Distributions of the $\alpha$ parameter after all other image cuts. The solid and dashed lines in the upper panels show the on-source and off-source results, respectively. The lower panels represent the on-off counts of the upper panels.](image-url)
mate the systematic error in determining the absolute threshold energies to be about 40%–50%. However, because almost all of the systematic errors behave in the same way for the three years’ observations, the uncertainty of the relative threshold energy is smaller than this value.

3.3. Consistency and Stability

A positive indication is obtained only from the lowest threshold energy observation. However, the derived flux and two flux upper limits require neither variability of the source nor a very soft spectral index; that is, the results from the three years are consistent with each other assuming stable emission with a Crab-like spectral index ($\sim 2.5$) or the harder index (1.8) expected by du Plessis et al. (1995). We also divided the 1997 data into separate new moon periods to check on consistency. The results are shown in Table 1. Each month’s result has a marginal positive effect on the final result. The excess counting rate is stable during the three observation seasons within the statistical errors.

3.4. Spatial Analysis

PSR B1509−58 and its surrounding environment are complex, and there are indications from X-ray data that nonthermal phenomena possibly occur over an extended area of this remnant. Thus, it is possible that the gamma-ray-like signal in the 1997 data is not from a point source at the pulsar position but from some other region near the pulsar. Therefore, we have carried out a source search in the $2^\circ \times 2^\circ$ field of view centered on the pulsar position. To do this, we shifted the position of the assumed source over a grid of points around the pulsar and repeated the analysis at each point to obtain the excess counts in the $\alpha$ distribution. The resultant map of the significance is shown in Figure 2.

The peak of the excess is found at 0:1 southwest from the pulsar. However, when we consider the degrees of freedom of the search, the significance at this maximum should be reduced. In addition, from a Monte Carlo calculation, where the observed counts of signal and background are taken into account, we estimated that the precision to determine the source position is 0:1 at the 1 $\sigma$ level. We conclude, therefore, that the position of the excess is consistent with the pulsar position within the statistics of our observations.

3.5. Periodicity Analysis

The recorded arrival times of the gamma-ray-like signals ($\alpha \leq 10^\circ$ after all the image cuts) were converted to the solar system barycenter arrival times using the solar system ephemeris based on epoch 2000 (DE200) (Standish 1982). We then carried out a phase analysis with the phase parameters summarized in Table 2 (Manchester et al. 1998). Because Nel et al. (1990) pointed out the possibility of a light curve with triple peaks in the TeV energy range, we applied the $H$-test (de Jager, Swanepoel, & Raubenheimer 1989) to obtain the statistical significance. The virtue of the $H$-test lies in the fact that it requires no assumptions about

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**Fig. 2.** Contour map of the significance around the pulsar position in the 1997 data. North is up and east is to the left. The field of view is $2^\circ \times 2^\circ$, and the pulsar position is indicated by the cross. The distance from the pulsar position to the peak of the excess (southwest from the pulsar) is 0:1 and is consistent with the pulsar position within the source localization error, which is indicated by the circle.
The results of 1997 are divided into separate observational periods (months) because GPS timing information was not available in 1997, as mentioned in § 2. The relative arrival time of the events is calculated for the 1997 data from the time of the crystal clock, which has a constant drift rate relative to the GPS clock. The H-statistics and the corresponding probabilities against a uniform distribution are shown in Table 3. No evidence for the 150 ms periodicity is found in any of the observation seasons. To calculate the flux upper limit for the pulsed emission, we used the formula given by de Jager (1994). This formula combines the observed counts (N) and pulsed fraction (p) through a parameter χ as χ = p/√N. When the H-statistic is considered a non-detection of periodicity, χ giving a 3σ upper limit of p is expressed as

\[ \chi_{3\sigma} = (1.5 + 10.7\delta)[0.174H]^{0.170 + 0.143} \times \exp \left\{ (0.08 + 0.156)[\log_{10}(0.174H)]^2 \right\} . \]

Here, H is the value of the H-test as shown in Table 3. (For H < 0.3 we should take H = 0.3 in calculating \( \chi_{3\sigma} \).) \( \delta \) is the duty cycle of the pulse profile. In the case of PSR B1509–58, we assumed \( \delta \) to be 0.3 using the X-ray observation by Kawai et al. (1991). The 3σ upper limits for the pulsed VHE gamma-ray emission are also shown in Table 3.

4. DISCUSSION

Our observations can be summarized as follows. (1) In the observations with the lowest detection threshold energy, a 4.1σ excess of gamma-ray-like events is found. Null results in the observations of the other years (when the detection threshold energies were higher) are not in conflict with this marginal positive result: neither variability of the source nor an especially soft energy spectrum needs to be invoked. (2) From the result in the 1997 observations, there is no evidence of a variability on a monthly timescale during three observation seasons. (3) In the 1997 data, the peak emission source position is shifted slightly to the southwest direction from the pulsar position. However, considering the statistical error including the real event numbers observed, this is consistent with the pulsar position. (4) The periodicity of the events modulated with the radio pulsar period is studied. We found no evidence of the 150 ms pulsar periodicity using the H-test in any of the observations for three years.

The statistical significance of the 1997 excess, 4.1σ, is too small to claim as the detection of a VHE gamma-ray source; however, it is sufficiently suggestive to allow discussion supposing the excess was due to a VHE gamma-ray signal. With this scheme the simplest and most straightforward explanation can be made assuming that the emission is found from the pulsar nebula surrounding the pulsar. VHE gamma-ray emission from a pulsar nebula is usually considered a result of inverse Compton scattering by relativistic electrons. From the emission processes of synchrotron and inverse Compton radiations, a simple equation, \( \frac{E_{\text{synch}}}{E_{\text{iC}}} = \frac{\epsilon_0}{\epsilon_{\text{ph}}/E_{\text{ph}}} \), can be obtained. Here \( E_{\text{synch}} \) and \( E_{\text{iC}} \) are the luminosities through synchrotron radiation (mainly resulting in quanta in the X-ray energy range) and inverse Compton scattering (mainly producing VHE gamma rays), respectively, and \( \epsilon_0 \) and \( \epsilon_{\text{ph}} \) are the energy densities of the magnetic field and the target photons for inverse Compton scattering at the emission region. Assuming isotropic emission of both X-rays and gamma rays, \( \frac{E_{\text{synch}}}{E_{\text{iC}}} \) can be equated to \( \frac{F_{\text{synch}}}{F_{\text{iC}}} \). Here \( F_{\text{synch}} = 7.2 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}(0.1-24 \text{ keV}) \) as given by Trussoni et al. (1996) and \( F_{\text{iC}} = 2.7 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1} \), obtained by integrating the 1997 flux above 1.9 TeV assuming a differential spectral index of 2.5. (The corresponding luminosity at the pulsar, \( L_{\text{iC}} \), is 6.2 \times 10^{34} \text{ ergs s}^{-1} \) assuming the pulsar distance of 4.4 kpc. That is 0.34% of the pulsar rotating energy loss.) If the 3 K microwave background radiation (MBR) is the only target of the inverse Compton radiation, i.e., \( \epsilon_{\text{ph}} = \epsilon_{\text{3 K}} = 3.8 \times 10^{-13} \text{ ergs cm}^{-3} \), one obtains \( \epsilon_{\text{0}} = 1.0 \times 10^{-12} \text{ ergs cm}^{-3} \). This, then, leads to a value for the magnetic field strength \( B \approx 5 \mu G \). Considering the large uncertainties in the arguments above, this value agrees well with the previously estimated value of \( B \approx 7 \mu G \) from the equipartition of energy between the particles and the magnetic field (Seward et al. 1984). According to the prediction of du Plessis et al. (1995), our result corresponds to a magnetic field strength of \( B \approx 5 \mu G \). These three estimated values of the magnetic field agree very well with each other.

An alternative source of the target photons is the IR source IRAS 15099–5856, known to be positionally coincident with the pulsar (Arendt 1991). Du Plessis et al. (1995) estimated that the contribution from the IR photons to the VHE gamma-ray flux would be at the same level as that from the 3 K MBR. However, the association between IRAS 15099–5856 and the pulsar is uncertain. In the case where the IRAS source found at 25 μm supplies the target photon for the inverse Compton process, the resultant VHE gamma-ray spectrum is expected to be softer than that made from the 3 K MBR. This is because the critical energy of the parent electrons in the Klein-Nishina cross section is
$\sim 6 \times 10^{12}$ eV against 25 $\mu$m IR radiation while it is $\sim 10^{15}$ eV for the 3 K MBR. Therefore, the VHE gamma-ray spectrum should have a rapid softening over the TeV energy range. To understand the association of this IRAS source, detailed spectral measurements with future observations are required as well as the X-ray observations discussed below.

While our observations do not place any interesting limit on the spectral index, the very hard spectrum predicted by du Plessis et al. (1995) should be discussed. Their prediction was based on the observational results of the X-ray spectrum, which showed a hardening of the index in the energy range below a few keV (photon index $1.4 \pm 0.4$ below 4 keV while 2.15 $\pm$ 0.02 between 2 and 60 keV). However, recent X-ray observations do not confirm this hardening. The photon indexes obtained in the wide X-ray energy band are consistent with a value around 2.2 (Trussoni et al. 1996; K. Tamura 1997, private communication; Marsden et al. 1997), though the error of the ROSAT result is large. To discuss the synchrotron spectrum in detail, we need information from radio observations. However, even with the recent high-resolution observations, a radio pulsar wind nebula has not been discovered (Gaensler et al. 1999).

The upper limits set to the periodic signal in this paper are 1 order of magnitude below the previously reported flux in the same energy band (Nel et al. 1992). Although Nel et al. reported upper limits from observations after 1988, our results should provide a far stricter limit on models. The VHE pulsed emission is in conflict with the observed cutoff around 10 MeV as predicted by the polar cap model. To explain the VHE pulsed emission, an additional hard component, probably outer gap emission, is required. Future observations by the Gamma-Ray Large-Area Telescope (GLAST) may reveal the existence of this component, and studies of its flux and spectral variability may hint at large variability in the VHE range. The flux of the transient VHE pulsed emission reported in 1985, $F(E \geq 1.5$ TeV) $= (3.9 \pm 0.9) \times 10^{-11}$ cm$^{-2}$ s$^{-1}$, would make this source the brightest known VHE gamma-ray source in the southern hemisphere. We could detect this kind of activity even with short-duration monitoring. Semisimultaneous monitoring of this pulsar with the future large IACT arrays in the southern hemisphere (CANGAROO-III, HESS) and GLAST would be of great interest if the pulsar were to display such an active phase in the future.

Finally, it is notable that, unlike the other pulsar nebulae detected at VHE energies, PSR B1509–58 is not firmly detected by EGRET on board the Compton Gamma-Ray Observatory. In contrast, this pulsar and its surroundings show a variety of nonthermal phenomena as introduced in § 1. A comparison of nonthermal X-ray emission with VHE gamma-ray emission is becoming very useful in the search for VHE gamma-ray sources and study of their environment. Combined with the recent studies of pulsar nebulae (Kawai & Tamura 1996), the new generation of imaging atmospheric Cerenkov telescopes (e.g., Matsubara et al. 1997) will result in an improved understanding of pulsar nebulae and particle acceleration. The CANGAROO II 7 m telescope started observations at Woomera in mid-1999. From new observations with a lower energy threshold, we will be able to measure the gamma-ray spectrum precisely and obtain a better estimation of the physical parameters, especially the magnetic field strength, in pulsar nebulae.

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