DISCOVERY OF PULSATIONS FROM THE PULSAR J0205+6449 IN SNR 3C 58 WITH THE FERMI GAMMA-RAY SPACE TELESCOPE

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ABSTRACT

We report the discovery of γ-ray pulsations (≥ 0.1 GeV) from the young radio and X-ray pulsar PSR J0205+6449 located in the Galactic supernova remnant 3C 58. Data in the γ-ray band were acquired by the Large Area Telescope aboard the *Fermi Gamma-ray Space Telescope* (formerly GLAST), while the radio rotational ephemeris used to fold γ-rays was obtained using both the Green Bank Telescope and the Lovell telescope at Jodrell Bank. The light curve consists of two peaks separated by $0.49 \pm 0.01 \pm 0.01$ cycles which are aligned with the X-ray peaks. The first γ-ray peak trails the radio pulse by $0.08 \pm 0.01 \pm 0.01$, while its amplitude decreases with increasing energy as for the other γ-ray pulsars. Spectral analysis of the pulsed γ-ray emission suggests a simple power law of index $-2.1 \pm 0.1 \pm 0.2$ with an exponential cut-off at $3.0^{+1.1}_{-0.7} \pm 0.4$ GeV. The first uncertainty is statistical and the second is systematic. The integral γ-ray photon flux above 0.1 GeV is $(13.7 \pm 1.4 \pm 3.0) \times 10^{-8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which implies for a distance of 3.2 kpc and assuming a broad fan-like beam a luminosity of $8.3 \times 10^{34}\,\mathrm{ergs\,s}^{-1}$ and an efficiency η of 0.3%. Finally, we report a 95% upper limit on the flux of $1.7 \times 10^{-8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for off-pulse emission from the object.

Subject headings: pulsars: general — stars: neutron

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1. INTRODUCTION

The radio source 3C 58 was recognized early to be a supernova remnant (SNR G130.7+3.1; Caswell 1970), and subsequently classified as a pulsar wind nebula (PWN, also plerion) by (Weiler & Panagia 1978). Becker et al. (1982) identified an X-ray point source in the heart of 3C 58 as a likely pulsar, and subsequent studies yielded a distance of 3.2 kpc (Roberts et al. 1993). The pulsar J0205+6449 was finally discovered in *Chandra X-ray*

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Observatory data, with a period of 65.7 ms, while *Rossi X-ray Timing Explorer* archives allowed a measurement of the spindown rate of $\dot{P} = 1.93 \times 10^{-13}$ (Murray et al. 2002). Both telescopes observed an X-ray profile with two narrow peaks separated by 0.5 in phase. This was followed by the detection of weak radio pulsations with a pulse averaged flux density of $\sim 45\,\mu$Jy at 1.4 GHz and a sharp pulse of width 2 ms (Camilo et al. 2002). The pulsar has a very high spin-down luminosity of $2.7 \times 10^{37}\,\mathrm{ergs\,s^{-1}}$ (the third most energetic of the known Galactic pulsars), a surface magnetic field strength of 3.6×10^{12} G, and a characteristic age of 5400 years. It also exhibits a high level of timing noise (Ransom et al. 2004), and at least two glitches have occurred since its discovery (Livingstone et al. 2008). Recently, a study by Livingstone et al. (2009) presented the first measurement of the phase offset between the radio and X-ray pulse, showing that the first X-ray peak lags the radio pulse by $\phi = 0.10 \pm 0.01$.

The 3C 58/J0205+6449 system coincides positionally with the 828-year-old historical supernova SN 1181 according to Stephenson (1971) and Stephenson & Green (2002). However, recent investigations of models for the PWN (Chevalier 2005) and the velocities of both the radio expansion (Bietenholz 2006) and optical knots (Fesen et al. 2008) imply an age for 3C 58 of several thousand years, closer to the characteristic age of the pulsar than of SN 1181. 3C 58 is similar to the apparently comparably aged Crab nebula (remnant of SN 1054) both having a flat-spectrum radio nebula, non-thermal extended X-ray emission, and point-like X-ray emission due to a central pulsar. But the two objects differ significantly both in luminosity and in size. The radio nebula of 3C 58, although $\sim$ 2 times larger, is less luminous than the Crab by an order of magnitude (Ivanov et al. 2004), while its X-ray luminosity is $\sim$ 2000 times smaller (Torii et al. 2000). These disparities could be explained by a different age.

2. OBSERVATIONS

2.1. *Radio Timing Observations*

As part of the space and ground based timing program supporting *Fermi* (Smith et al. 2008), PSR J0205+6449 is being observed at the NRAO Green Bank Telescope (GBT) and the Lovell telescope at Jodrell Bank. The GBT provides higher precision data, but observations are made more frequently at Jodrell Bank, and the rotational ephemeris used here to fold gamma-ray photons is based on times-of-arrival (TOAs) obtained from both telescopes between 2008 June 17 and 2009 March

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9. There are 17 such TOAs from GBT mainly at a central frequency of 2.0 GHz, with average uncertainty of 0.27 ms, each based on a 1 hr integration. The 51 Jodrell Bank TOAs, with average uncertainty of 0.37 ms, are derived from observations at 1.4 GHz lasting typically for 2 hr. The timing of PSR J0205+6449 is very noisy, and in order to describe its rotation well during the 9 month interval we use TEMPO[57] to fit to the rotation frequency and its first seven derivatives, with an rms of 0.4 ms. The best determination of dispersion measure (DM = 140.7 ± 0.3 pc cm^{-3}) remains that from Camilo et al. (2002), which we use to correct 2 GHz arrival times to infinite frequency, with an uncertainty of 0.3 ms, for comparison with the gamma-ray profile. Note that higher signal-to-noise ratio profiles of the pulsar are presented at 0.8 and 1.4 GHz in Camilo et al. (2002).

2.2. *Gamma-Ray Observations*

The Large Area Telescope (LAT) on *Fermi*, launched on 2008 June 11, is a pair-conversion telescope consisting of 16 towers set into a 4×4 grid (Atwood et al. 2009). Each tower consists of both a converter-tracker (direction measurement of the incident γ-rays) and a CsI(Tl) crystal calorimeter (energy measurement/shower development image). The array is surrounded by segmented plastic scintillator (charged-particle background identification) and connected to a programmable trigger and data acquisition system. The instrument is sensitive to photons from 0.02 to 300 GeV over a ~ 2.4 sr field of view resulting from the compact height/width ratio of the instrument. The LAT hardware design, event reconstruction algorithms, background selections and event quality selections determine the instrument performance[58]: a large effective area on axis (~ 0.8 m^2); superior angular resolution ($\theta_{68} \sim 0.5°$ at 1 GeV for events in the front section of the tracker); and an energy resolution better than 10% between 0.1 and 10 GeV on axis. The software timing chain deriving from a GPS clock on the satellite and the phase-folding software have been shown to be accurate to better than a few μs (Smith et al. 2008).

In this letter, the data collected for the timing analysis were obtained by the *Fermi* LAT in two different observing modes, from 2008 July 15 to July 29 during the six-week calibration phase, and from 2008 August 3 to 2009 March 9 when LAT was operating in scanning mode under nominal configuration. For the spectral analysis, only data acquired from 2008 August 3 were used to avoid mixing the different configurations. We used the "Diffuse" class events having the highest probability of being photons. In addition, we excluded the events with zenith angles greater than 105° due to the Earth's bright γ-ray albedo, and time periods where the Earth's limb came within 28° of the source.

3. ANALYSIS AND RESULTS

The events were analyzed using the standard software package *Science Tools* (ST) for the *Fermi* LAT data analysis[59] and the pulsar timing software TEMPO2 (Hobbs et al. 2006). The timing parameters used in this

work will be made available on the servers of the *Fermi* Science Support Center[60].

3.1. *Pulsed Light Curve*

The pulsar is located in the Galactic plane where the diffuse gamma radiation is intense, and 5.3° from the bright LAT source 0FGL J0240.3+6113 coincident with the X-ray binary LSI+61°303 (Abdo et al. 2009a). For the timing analysis, a set of photons with energies over 0.1 GeV was selected within an energy-dependent cone of radius $\theta_{68} \leqslant 0.8 \times E_{\mathrm{GeV}}^{-0.75}$ degrees, but with a maximum radius of 1.5° with respect to the X-ray pulsar position ($l = 130.719°$, $b = 3.085°$). This choice takes into account the instrument performance and maximizes the signal-to-noise ratio over a broad energy range. This truncates the point spread function at low energies and decreases the number of background events (Atwood et al. 2009). A total of 2922 γ-rays remain after these cuts. The arrival times of events were corrected to the Solar System Barycenter using the JPL DE405 Solar System ephemeris (Standish 1998), and the events have been folded using the radio ephemeris from GBT and the Lovell telescope at Jodrell Bank.

Figure 1 (top panel) shows the 50 bin γ-ray phase histogram on which we fit each peak. The first peak (P1) is offset from the radio pulse (bottom panel) by $0.08 \pm 0.01 \pm 0.01$ according to a Lorentzian fit with a full width at half maximum (FWHM) of 0.15 ± 0.03. The first phase uncertainty arises from the γ-ray fit, and the second is from the DM uncertainty in extrapolating the radio time-of-arrival to infinite frequency. The second peak (P2) is asymmetric, fit by a two-sided Lorentzian to take into account the different widths for the leading and trailing edges. The fit places the peak at $0.57 \pm 0.01 \pm 0.01$ with an FWHM of 0.13 ± 0.04. The two peaks are separated by $0.49 \pm 0.01 \pm 0.01$ in phase. We defined the 'off pulse region' as the pulse minimum between 0.65 and 1.0 in phase. The dashed line in Figure 1 represents the background counts measured from a $2 - 3°$ ring surrounding the pulsar during the pulse minimum. Evidence for an excess between P1 and P2 appears with a significance (signal/$\sqrt{\text{background}}$) of $5.0\,\sigma$ between 0.14 and 0.46 in phase. However, the data cannot constrain the pulse phase dependence of this excess flux.

To examine the energy-dependent trend of the γ-ray pulse profile, 50 bin phase histograms are plotted in three energy intervals, $0.1 - 0.3$ GeV, $0.3 - 1$ GeV, and ≥ 1 GeV in Figure 1 (middle panels), which show an evolution in the shape. Between 0.1 and 1 GeV, we see distinctly two peaks and a possible bridge region in excess of the unpulsed emission, while above 1 GeV only P2 is significant. We also observe that the ratio P1/P2 (sum of counts) decreases with increasing energy, with a ratio of 0.63 ± 0.06 between $0.1 - 0.3$ GeV, 0.55 ± 0.05 between $0.3 - 1.0$ and 0.24 ± 0.06 above 1 GeV. The Vela (Abdo et al. 2009b), Crab, Geminga and B1951+32 pulsars show similar behavior (Thompson 2001). This general trend suggests a spectral energy dependence of the γ-ray light curve. Finally, we note that the highest energy photon is in P2 with an energy of 8.6 GeV.

Figure 1 (bottom panels) also shows the $2 - 60$ keV X-ray phase histogram measured by *RXTE*

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[57] http://www.atnf.csiro.au/research/pulsar/tempo/
[58] http://www−glast.slac.stanford.edu/software/IS/glast_lat_performance.htm
[59] http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/overview.html [60] http://fermi.gsfc.nasa.gov/ssc/data/access/lat/ephems/
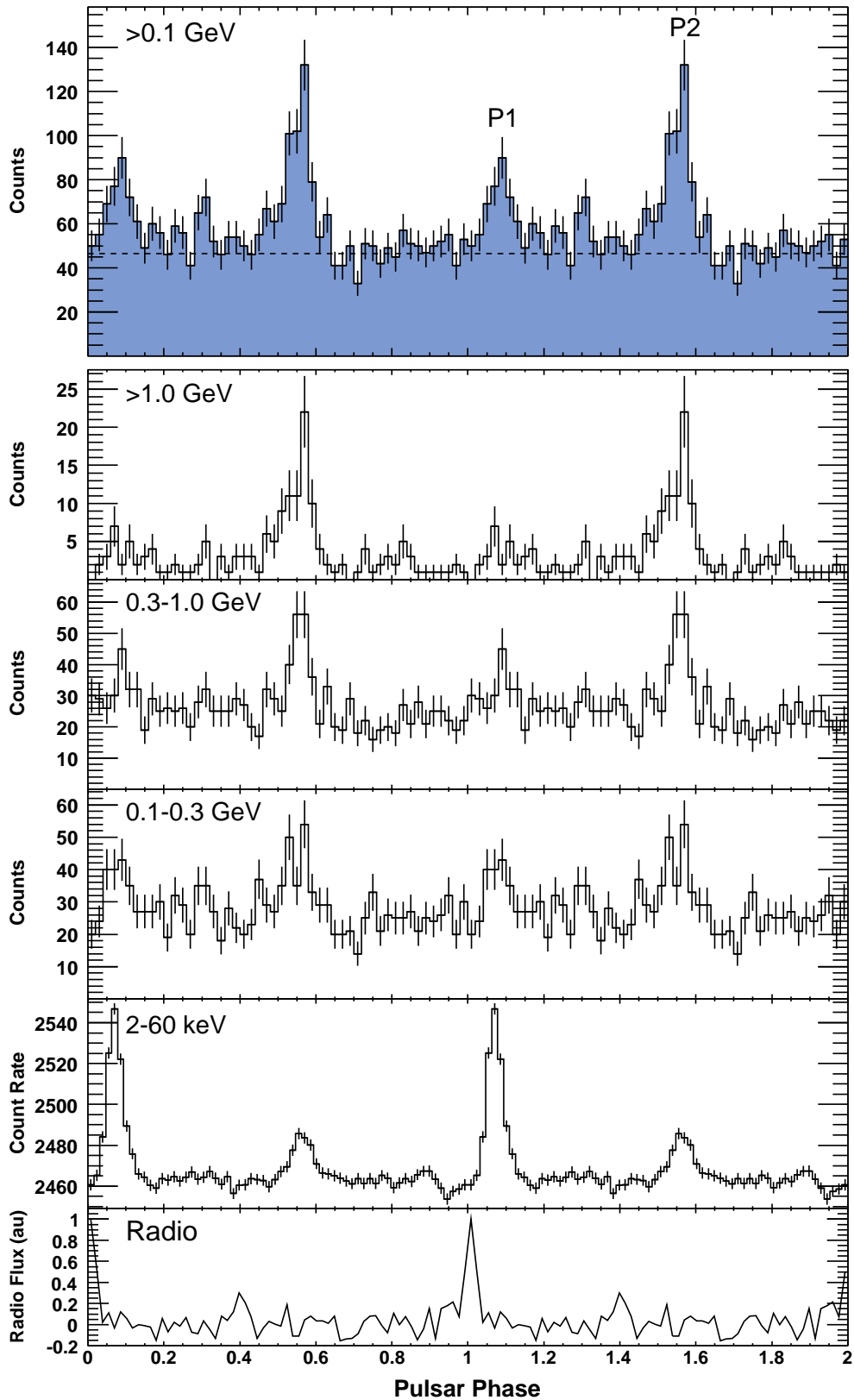
FIG. 1.— **Top panel:** Phase-aligned histogram of PSR J0205+6449 above 0.1 GeV and within an energy-dependent circle. Two rotations are plotted with 50 bins per period. The dashed line shows the background level, as estimated from a ring surrounding the pulsar during the off-pulse phase (46 counts/bin). **Three following panels:** Energy dependent phase histograms for PSR J0205+6449 in the three indicated energy ranges, each displayed with 50 bins per pulse period. **Second panel from bottom:** Count rate in the energy band 2−60 keV from *RXTE* data (Livingstone et al. 2009). **Bottom panel:** Radio pulse profile based on 3.8 hours of GBT observations at a center frequency of 2 GHz with 64 phase bins.

(Livingstone et al. 2009) as well as the 2 GHz radio profile from GBT (the single peak defines phase $\phi = 0$). Livingstone et al. (2009) find that the radio pulse leads the X-ray pulse by $\phi = 0.10 \pm 0.01$ and note a separation between the two narrow X-ray peaks of $\Delta\phi = 0.5$. The good alignment between the X-ray and γ-ray profiles suggests a common origin between the two components. This feature is also observed in the LAT data for the Vela pulsar where the more intense X-ray pulse is aligned with the first γ-ray pulse (Abdo et al. 2009b).

3.2. Spectra and phase-averaged flux

To study the phase-averaged spectrum of J0205+6449, a maximum likelihood spectral analysis[61] (Mattox et al. 1996), implemented in the ST as the *gtlike* task, was performed using a $20°$ γ-ray map centered on the pulsar position between 0.1 and 200 GeV. The systematic errors on the effective area are currently estimated as $\leq 5\%$ near 1 GeV, 10% below 0.1 GeV and 20% above 10 GeV. The diffuse emission from the Galactic plane was modeled using maps based on the GALPROP model (gll_iem_v01) (Strong et al. 2004a,b). The extragalactic radiation as well as the instrumental backgrounds were modeled by an isotropic component with a power-law spectral shape. Nearby LAT sources were included in the analysis. For PSR J0205+6449, we modeled the shape of the spectrum with a power law with an exponential cut-off.

We first determined the diffuse background components by selecting off-pulse data. Then, we fitted the on-pulse data using the diffuse background spectrum thus obtained in order to improve the signal-to-background ratio of the pulsar and the nearby sources. The best fit result is described by:

$$\frac{dF}{dE} = N_0 \, E^{-\Gamma} \, e^{-E/E_c} \; \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1} \qquad (1)$$

with E in GeV, the term $N_0 = (1.4 \pm 0.1 \pm 0.1) \times 10^{-8} \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1} \, \mathrm{GeV}^{-1}$, the spectral index $\Gamma = 2.1 \pm 0.1 \pm 0.2$, and the cut-off energy $E_c = 3.0^{+1.1}_{-0.7} \pm 0.4$ GeV. The errors are the statistical and propagated systematic uncertainties, respectively. We obtain from this fit over the range 0.1–200 GeV an integral photon flux of $(13.7 \pm 1.4 \pm 3.0) \times 10^{-8} \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$ and integral energy flux of $F_{E,obs} = (6.7 \pm 0.5 \pm 1.0) \times 10^{-11} \, \mathrm{ergs\,cm}^{-2} \, \mathrm{s}^{-1}$. To check the assumption of a cut-off energy in the spectrum, we have also fit the same dataset with a simple power-law of the form $dF/dE = N_0(E/1\mathrm{GeV})^{-\Gamma}$. The spectral model using an exponential cut-off is better constrained with a difference between the log likelihoods of $\sim 4.5\,\sigma$, disfavoring the power-law hypothesis. The source, having a statistical significance of $9.5\,\sigma$ ($< 10\,\sigma$) from 0.2 to 100 GeV for the first three months of the sky survey in the science phase of the mission, does not appear in the *Fermi* LAT bright γ-ray source list (Abdo et al. 2009a).

As a first search for unpulsed emission from the nebula 3C 58, we fitted a point-source to the off-pulse data at the radio pulsar position in the energy band 0.2 – 200 GeV. No signal was observed from the PWN. Lastly, after scaling to the full pulse phase, we derived a 95% CL upper limit on the flux of $1.7 \times 10^{-8} \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$.

4. DISCUSSION

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[61] http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/

4.1. Light curve

Multi-wavelength light curves are important to locate the pulse emission in the open field line region and hence to understand the mechanisms of particle acceleration. The γ-ray profile for J0205+6449, covering a wide range in phase, is reminiscent of the Vela light curve (Abdo et al. 2009b), including the γ-ray peak alignment with the X-ray pulses. The γ-ray delay of 0.08 cycles and the peak separation of ~ 0.5 is becoming a consistent pattern, as the first γ-ray peaks for Vela, B1951+32, and J2021+3651 (Halpern et al. 2008; Abdo et al. 2009c) lag the radio pulses by 0.13, 0.16, and 0.17 respectively, and the separation of the γ-ray peaks is 0.4 – 0.5. This fits the predictions of the outer magnetospheric models quite well, whether they be the traditional outer gap model (OG) (Romani & Yadigaroglu 1995) or the two pole caustic gap model (TPC) (Dyks & Rudak 2003).

4.2. Beaming and Luminosity

To know the γ-ray efficiency, we need to determine the total luminosity $L_\gamma = 4\pi f_\Omega(\alpha, \zeta_E) \, F_{E,obs} D^2$, where D is the distance to the pulsar, $F_{E,obs}$ is the observed phase-averaged energy flux for the Earth line of sight (at angle ζ_E to the rotation axis), and $f_\Omega(\alpha, \zeta_E)$ is a correction factor that takes into account the beaming geometry, given by (Watters et al. 2008):

$$f_\Omega(\alpha, \zeta_E) = \frac{\int F_\gamma(\alpha; \zeta, \phi) sin(\zeta) d\zeta d\phi}{2 \int F_\gamma(\alpha; \zeta_E, \phi) d\phi} \qquad (2)$$

where $F_\gamma(\alpha; \zeta, \phi)$ is the radiated flux as a function of the viewing angle (ζ) and the pulsar phase (ϕ), while f_Ω is the ratio between the overall γ-ray emission over the full sky and the expected phase-averaged flux for the light curve seen from the Earth. In the case of a polar cap model (Harding 2005) where charged particles are accelerated in charge-depleted zones near the poles of the pulsar, $f_\Omega \ll 1$, while for the outer magnetosphere models the emission is radiated with $f_\Omega \gtrsim 1$.

An important uncertainty when evaluating the γ-ray efficiency arises from the determination of the distance. Observations of neutral hydrogen (H I) absorption by Roberts et al. (1993) yielded an estimate for the radial velocity of 3C 58. They convert this to a kinematical distance of 3.2 kpc assuming a flat Galactic rotation curve as per Fich et al. (1989), who quotes distance uncertainties of order 25%, making this result consistent with the 2.6 kpc previously reported by Green & Gull (1982). The distance derived from the DM is 4.5 kpc, according to the NE 2001 model (Cordes & Lazio 2002), with an uncertainty that can exceed 50%, depending on the viewing direction, consistent with the kinematical distance.

We estimate $L_\gamma = 8.3 \times 10^{34} \, (D/3.2\,\mathrm{kpc})^2 \, f_\Omega \, \mathrm{ergs\,s}^{-1}$, and deduce, for a neutron star moment of inertia of $10^{45} \, \mathrm{g\,cm}^2$, a γ-ray efficiency $\eta = L_\gamma/\dot{E} = 0.003 \, f_\Omega \, (D/3.2\,\mathrm{kpc})^2$. Assuming the outer magnetospheric models for PSR J0205+6449, we can deduce the parameters α and ζ from the γ-ray peak separation and using the γ-ray light curve "Atlas" of Watters et al. (2008). For the OG model, we estimate $f_\Omega \approx 0.9$–1.0 with $\alpha \backsim 60°$–$90°$ and $\zeta \backsim 80°$–$85°$, while for the TPC model, $f_\Omega \approx 0.95$–1.25 with both $\alpha \backsim 50°$–$90°$, $\zeta \backsim 85°$–$90°$ and $\alpha \backsim 85°$–$90°$, $\zeta \backsim 45°$–$90°$. Examination of the geometry of the PWN 3C 58 using *Chandra*

(Ng & Romani 2004, 2008) yielded a viewing angle of $\zeta = 91.6 \pm 0.2 \pm 2.5$ ° (inner torus) based on the tilt angle of the torus to the plane of the sky. This value is in agreement with the results from the OG model and more consistent with the first estimated range for the TPC model. Adopting an average value for $f_\Omega = 1$ according to the OG model and a distance of 3.2 kpc, we evaluate a γ-ray efficiency $\eta = 0.3\%$ for converting its rotational energy loss into γ-rays.

Studies of rotation powered pulsars suggest that the efficiency η for converting its rotational energy loss into γ-rays increases as the open field line voltage $V \simeq 4 \times 10^{20} P^{-3/2} \dot{P}^{1/2}$ volts decreases and is proportional to $\dot{E}^{-1/2}$ (Arons 1996). V is also proportional to the open field current (Harding 1981) and to the characteristic age of the pulsar (Buccheri et al. 1978). We note that with an open field line voltage of 1.0×10^{16} V, that PSR J0205+6449 closely follows the approximate $\eta \propto \dot{E}^{-1/2} \propto 1/V$ relations, confirming the trend.

Thompson et al. (1999) point out that for the γ-ray EGRET pulsars the broadband energy spectra for the young pulsars like Crab and B1509−58 peaks in the X-ray band, while the older γ-ray pulsars have their maximum luminosity in the high-energy regime. Considering a X-ray luminosity between 0.5 and 8 keV of 1.51×10^{33} ergs s^{-1} (Kargaltsev & Pavlov 2008) and a gamma-ray luminosity of 8.3×10^{34} ergs s^{-1} with $f_\Omega = 1$, PSR J0205+6449 seems to have an $L_X/L\gamma$ ratio closer to the middle-aged Vela pulsar than the young Crab and B1509−58 pulsars, and hence suggests that the association of 3C 58 and historical supernova SN 1181 is probably incorrect.

5. SUMMARY

Using a rotational ephemeris derived from radio observations with the GBT and at Jodrell Bank, and γ-ray data from the *Fermi* LAT, we have discovered in the Galactic SNR 3C 58 γ-ray pulsations from PSR J0205+6449, the third most energetic of the known Galactic pulsars. This source has no EGRET counterpart and presents a new opportunity to study the pulsar/SNR association at high energies, demonstrating the good performance of the instrument.

1. The γ-ray profile for J0205+6449 is similar to the majority of known γ-ray pulsar light curves, in particular to the Vela pulsar. It consists of two peaks separated by $0.49 \pm 0.01 \pm 0.01$ in phase. The radio pulse leads the γ-ray pulse by $\phi = 0.08 \pm 0.01 \pm 0.01$ and the X-ray peaks are aligned with the γ-ray peaks.

2. We report a 95% CL upper limit on the flux of 1.7×10^{-8} cm^{-2} s^{-1} for a possible unpulsed emission from the nebula 3C 58.

3. The γ-ray energy spectrum above 0.1 GeV can be described by a simple power law with photon index of $2.1 \pm 0.1 \pm 0.2$ and an energy cut-off of $3.0^{+1.1}_{-0.7} \pm 0.4$ GeV.

4. Adopting a distance of 3.2 kpc and assuming a broad fan-like beam, we report an efficiency of $\sim 0.3\%$ for the conversion of spin-down energy into γ-ray emission.

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