Research in Astron. Astrophys. **2009** Vol. **9** No. **12**, 1324–1330
http://www.raa-journal.org *http://www.iop.org/journals/raa*

Research in Astronomy and Astrophysics

Studying the Fermi GeV light curve of Vela with the two-pole caustic model *

Huan Yu, Jun Fang and Ze-Jun Jiang

Department of Physics, Yunnan University, Kunming 650091, China; *fangjun1653@yahoo.cn*

Received 2009 June 22; accepted 2009 July 29

Abstract An observation of the Vela pulsar with the *Fermi* Large Area Telescope has been recently reported and the GeV light curve shows two main peaks with a phase separation of ~ 0.43. We study the GeV light curve using the two-pole caustic model in which the peaks of the light curves of the pulsar result from caustic effects. The results show that the two-pole caustic model can reproduce the observed emission pattern of the two peaks and the bridge emission between them well, but overestimates the flux outside the two peaks. After taking account of the pair production effect on the azimuthal angle, we find that the resulting light curve is more consistent with the observation. We excluded the emissions from the field lines for which the distance from the null charge surface, where the pairs can be significantly produced, is larger than the radius of the light cylinder.

Key words: gamma rays: theory — pulsars: individual (PSR B0833–45)

1 INTRODUCTION

The Vela pulsar (PSR B0833–45) exhibits broadband pulsed emission in the radio (Large et al. 1968; Dodson et al. 2003), optical (Caraveo et al. 2001), X-ray (Helfang et al. 2001; Pavlov et al. 2003) and γ-ray (Thompson et al. 1975; Kanbach et al. 1994; Abdo et al. 2009) bands with a period of $\sim$89 ms and a distance of ~ 287 pc (Dodson et al. 2003). Thompson et al. (1975) first reported the pulsed γ-rays from Vela detected in the *SAS 2* mission and showed that it is the brightest persistent γ-ray source. More elaborate detection of the source with the Energetic Gamma-Ray Experiment Telescope (EGRET) onboard the Compton Gamma-Ray Observatory (CGRO) indicated that two narrow γ-ray peaks appeared in the light curve (Kanbach et al. 1994). The two peaks have a separation of 0.42 in phase and the ratio of the leading peak (P1) to the trailing peak (P2) is > 1 in the energy range between 0.03 and 10 GeV. Very recently, the pulsar was observed with the Large Area Telescope (LAT) onboard the *Fermi* Gamma-Ray Space Telescope and 32 400 pulsed photons with energy > 0.03 GeV were received; the result shows that the ratio of the two narrow γ-ray peaks decreases with increasing energy; meanwhile, a third peak emerges between the two peaks and moves to a later phase with increasing energy (Abdo et al. 2009).

High-energy emission from pulsars can usually be interpreted by polar cap models (e.g., Daugherty & Harding 1982, 1994; Sturner et al. 1995), outer gap models (e.g., Romani & Yadigaroglu 1995; Zhang & Cheng 1997; Tang et al. 2008) and two-pole caustic (TPC) ones (Dyks & Rudak 2003; Dyks et al. 2004). In the polar cap model, the characteristics of the two peaks of the pulsar light curves are usually produced when the line of sight intersects the polar cap beam. At the same time, the model must use a nearly aligned rotator to reproduce the observed properties of the light curve (Daugherty & Harding

* Supported by the National Natural Science Foundation of China.

1994; Dyks & Rudak 2003). For the outer gap model and the TPC model, two dominating γ-ray peaks are due to the caustic effects which can make the high-energy photons emitted at different altitudes be observed at the same phase.

The high-energy light curve of Vela has already been studied with the TPC model by Dyks & Rudak (2003) and Dyks et al. (2004). They use the static dipole magnetic field for the Vela pulsar and the model light curve is compared with the EGRET result. Note that although Dyks et al. (2004) used the retarded vacuum dipole solution for the field of the magnetosphere to investigate the properties of the TPC model, they still applied the static field to produce the resulting light curve for Vela. In this paper, motivated by the new results obtained with the LAT onboard the *Fermi* Space Telescope, we reinvestigate the GeV light curve of the Vela pulsar using the TPC model, which includes the retardation of the magnetic field, and the aberration and time delay of the high-energy photons. In the model, the emission region is concentrated in the last open field lines emerging from the polar cap to the the light cylinder, and high-energy photons are produced tangentially to the field lines. As a result, the caustic effects lead the photons to accumulate in the pulsar phase. It is shown that the TPC model can produce the flux pattern between the two dominating peaks in the light curve obtained with the *Fermi* LAT. However, the model overestimates the emission outside the two peaks, which indicates that the high-energy GeV photons cannot all be from the last field lines. Moreover, it is shown that the resulting flux outside the two peaks can be greatly reduced if the emission from the field lines for which the distance of the null charge surface is bigger than the radius of the light cylinder is excluded and the light curve from the model is more consistent with the observation. In Section 2, the model is briefly introduced and the results for the Vela pulsar are displayed. Finally, the conclusions and some discussions are given in Section 3.

2 THE TPC MODEL

In the TPC model, a retarded vacuum dipole geometry of the magnetic field around the pulsar is assumed (the details of the retarded dipole can be seen in Cheng et al. 2000); the gap confined to the last open field lines is thin and extends from the polar cap to the light cylinder; high-energy photons are emitted along the field lines emerging from the star's surface to high altitudes and the emissivity is uniform within the gap region (Dyks & Rudak 2003; Dyks et al. 2004).

In the calculation, Runge-Kugga integrations are employed to obtain the shape of the polar cap rim. The open volume coordinates ($r_{\rm ovc}$, $l_{\rm ovc}$) are established to easily emulate the particle distributions at the pulsar surface, where $r_{\rm ovc} = 1 \pm d_{\rm ovc}$, $d_{\rm ovc}$ is the minimum distance of a point from the polar cap region in units of the standard polar cap radius, $l_{\rm ovc}$ is the arc length along the deformed ring of the fixed $r_{\rm ovc}$; the electron distribution is rim-dominated at the star's surface and can be expressed by a Gaussian function:

$$\frac{dN_{\rm ph}}{ds} \propto \exp\left(-\frac{(r_{\rm ovc} - r^0_{\rm ovc})^2}{2\sigma^2}\right), \tag{1}$$

with σ usually set to 0.025; the emission region has an upper boundary $r_{\rm max}$, which is the distance of the emission region to the star, and the emissivity drops to zero at a distance $\rho_{\rm max} = (0.75 - 0.95R_{\rm lc})$ from the rotational axis, where $R_{\rm lc}$ is the distance of the light cylinder (see details in Dyks et al. 2004).

The high-energy photons are emitted tangentially to local magnetic field lines in the corotating frame, and the direction $\boldsymbol{\eta}$ in the observer's frame can be obtained from the direction $\boldsymbol{\eta}'$ in the corotating frame with

$$\boldsymbol{\eta} = \frac{\boldsymbol{\eta}' + [\gamma + (\gamma - 1)(\boldsymbol{\beta} \cdot \boldsymbol{\eta}')/\beta^2]\boldsymbol{\beta}}{\gamma(1 + \boldsymbol{\beta} \cdot \boldsymbol{\eta}')}, \tag{2}$$

where $\gamma = (1 - \beta^2)^{-1/2}$, $\boldsymbol{\beta} = \boldsymbol{v}/c$, $\mathbf{v} = \boldsymbol{\Omega} \times \boldsymbol{r}$, $\boldsymbol{\Omega}$ is the angular velocity of the pulsar and $\boldsymbol{r}$ is the radial distance of the emission point (Dyks & Rudak 2003). Then, a phase of detection Φ can be obtained with

$$\Phi = -\phi_{\rm em} - \boldsymbol{r} \cdot \boldsymbol{\eta}/R_{\rm lc}, \tag{3}$$

where $\phi_{\rm em}$ is the azimuthal angle of $\boldsymbol{\eta}$.

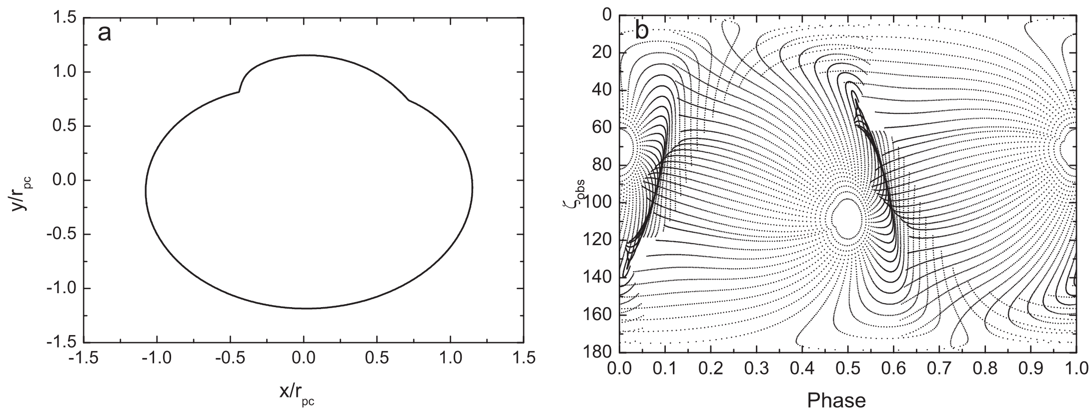

Fig. 1 (a) Shape of the polar cap. The positive x-axis corresponds to the magnetic azimuth = 0 and the rotation is counterclockwise. (b) Projection of the last open field lines on the space $(\Phi, \zeta_{\rm obs})$. The parameters are $\alpha = 71^\circ$, $r_{\rm ovc} = 1$, $r_{\rm max} = 0.95R_{\rm lc}$, $\rho_{\rm max} = 0.95R_{\rm lc}$, and $P = 89.3$ ms.

Figure 1 shows the shape of the polar cap and the projection of the last open field lines of the rotating retarded dipole on the space $(\Phi, \zeta_{\rm obs})$ for $\alpha = 71^\circ$, $r_{\rm ovc} = 1$, $r_{\rm max} = R_{\rm lc}$, $\rho_{\rm max} = 0.95R_{\rm lc}$, and $P = 89.3$ ms is the rotation period, $r_{\rm pc} = (\Omega R_{\rm ns}^3/c)^{1/2}$ is the standard polar cap radius, $R_{\rm ns} = 10^6$ cm is the radius of the star, α is the inclination angle of the dipole and $\zeta_{\rm obs}$ is the angle between the rotation axis and the observer's line of sight. Two notch points appear clearly in the polar cap (panel (a) in Fig. 1) and the two blank deformed ovals in the projection map correspond to the two polar caps. Two caustics can be seen as the dark areas in the figure (panel (b)) with phases of about –0.4 and 0.1, respectively. The two caustics are due to accumulation of photons within a broad range of altitudes, which is because the phase delay of photons emitted at high altitudes along a trailing field line is compensated by the effects of aberration and time of flight (Morini 1983).

The light curves predicted by the TPC model for different viewing angles are shown in Figure 2. Each curve in the figure is normalized by rescaling the peak flux to 1 with the same parameters as Figure 1. Two dominating peaks with a separation of 0.35 – 0.5 in phase can be produced with large viewing angles. The bump at $\Phi \sim -0.2$ for $\zeta_{\rm obs} \sim 60^\circ$ is due to the the accumulation of photons emitted from the field lines emerging from the notched part of the rim; the hollow part at phase ~ 0 for $\zeta_{\rm obs} \sim 70^\circ$ is produced when the line of sight crosses the polar cap region.

The initial observations of the Vela pulsar with the LAT on *Fermi* have been reported by Abdo et al. (2009). Two main narrow peaks, the first peak (P1) and the second peak (P2), appear in the GeV light curves with a phase separation of about 0.43 and the two peaks are asymmetric, i.e., P2 has a slow rise and a fast fall, whereas the fall of P1 is slower; moreover, a third peak in the bridge component becomes distinct at energies > 1 GeV and the peak moves to the later phase with increasing energy.

High-energy photons from pulsars can be produced via curvature radiation or inverse Compton scattering and those with energies above several GeV are usually attenuated via photon-photon interactions between the GeV photons and the ambient soft X-rays, either from the thermal star surface or from the magnetosphere (e.g., Tang et al. 2008); moreover, for photons with lower energy of several tens of MeV, the production is most probably via inverse Compton scattering, and the emissivity changes greatly with different positions in the magnetosphere. In the TPC model, the emissivity of the high-energy photons is assumed uniform along the magnetic field lines, and the attenuation of the photons is neglected, so the model is not applicable for photons with energy either above several GeV or below several tens of MeV. As a result, the light curve obtained with the *Fermi* LAT at energy 0.3–1 GeV is used to compare with the light curve predicted by the model (Fig. 3). Note that the phase 0 for the LAT data corresponds to the radio peak at 1.4 GHz, whereas in the model it corresponds to photons emitted at the stellar

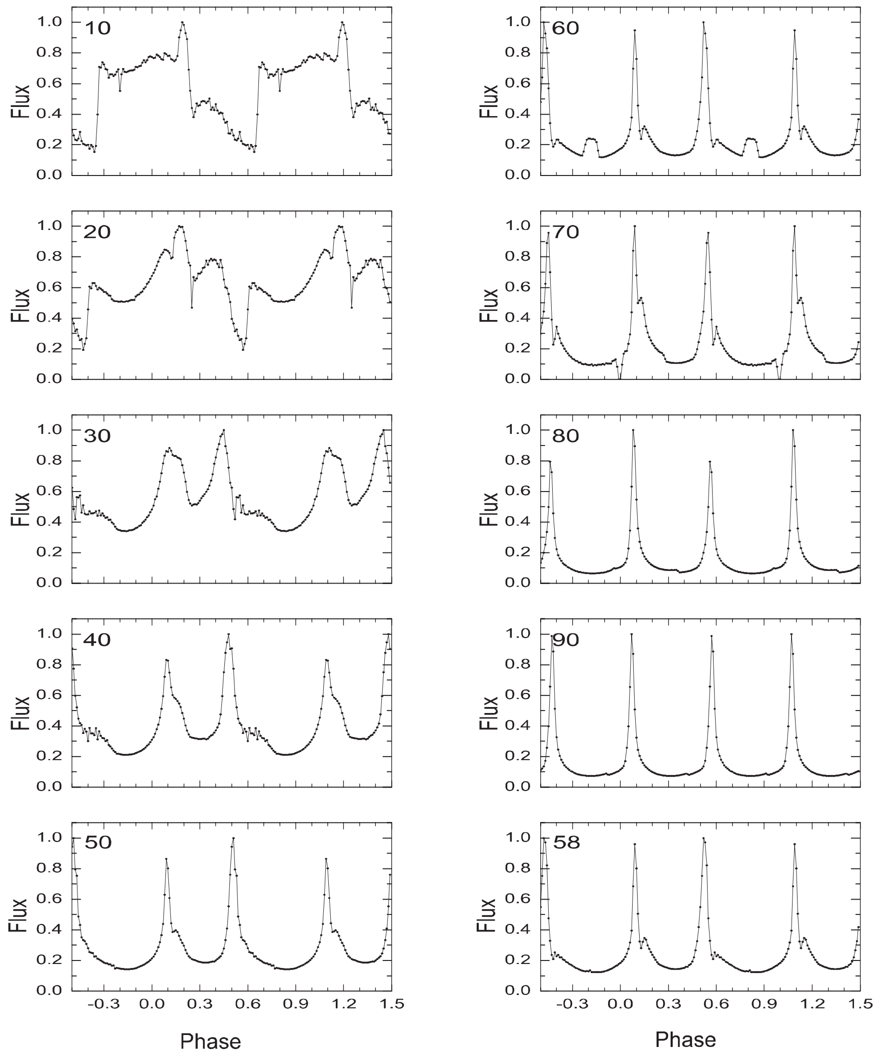

Fig. 2 Model light curves predicted by the TPC model for different viewing angles. The parameters are the same as Fig. 1.

center. Moreover, the altitude of the radio emission for a young, Vela-like pulsar can be 500–1000 km (Karastergiou & Johnston 2007). The bulk of the radio pulse and the high-energy one may originate from different field lines and their locations are usually different. Therefore, there is usually a phase difference between the resulting curve of the model and the observed one with the LAT, and we add a phase shift of 0.0425, which is chosen accordingly to make the first peak in the resulting curve align with the P1 of the *Fermi* curve, to the resulting curve for comparison (Fig. 3). Clearly, the model can successfully produce the shape of the two dominating peaks and the bridge emission between them: the ratio of P2 to P1, the phase separation of the two peaks, the steep outer edge of P1 and P2, a slow rise and a fast fall of P2, and the broad flux pattern of the bridge curve between the two peaks. However, the model overestimates the flux outside the two peaks, i.e., in the phase 0 – 0.12 and 0.56 – 1. The light curve in the two phase intervals corresponds to the emission at low altitudes in the trailing magnetic field lines and the emission from the leading field lines. The low fluxes in the two phase intervals suggest

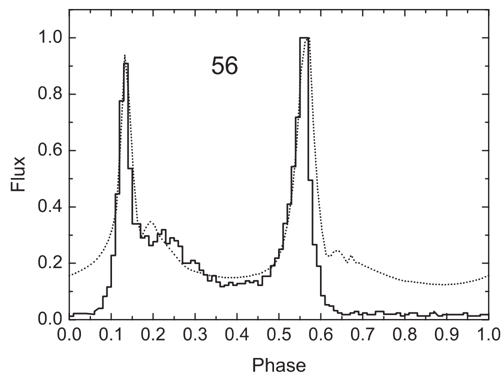

Fig. 3 Comparison of the light curve (*dotted line*) predicted by the TPC model for $\zeta_{\rm obs} = 56^\circ$ with the high-energy GeV light curve (*solid line*) in the band 0.3 – 1 GeV observed with the *Fermi* LAT (Abdo et al. 2009). Note that a phase shift of 0.0425 is added to the model curve to compare with the observed one in Abdo et al. (2009). The other parameters are the same as Fig. 1.

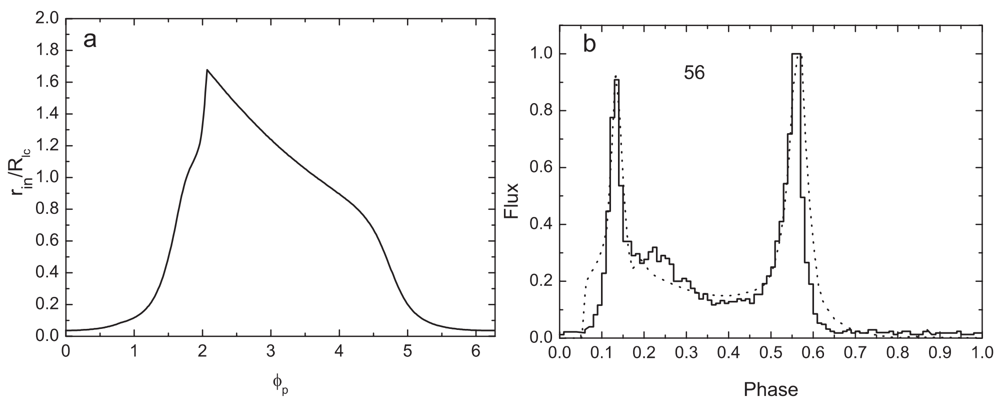

Fig. 4 (a) Radial distance to the null charge surface for the last open field lines, here $\phi_{\rm p}$ is the azimuthal angle of the polar cap. (b) Light curve (*dotted line*) predicted by the two-pole caustic model excluding the emission from the field lines for which $r_{\rm in} > R_{\rm lc}$. Others are the same as Fig. 3.

that GeV photons cannot be significantly produced along some last open field lines, which is possibly because particles cannot be effectively accelerated along those lines.

3 REVISED VERSION OF THE TPC MODEL

The light curve predicted by the TPC model in the off-pulse region is relatively high compared with the observation with the LAT on *Fermi* (see Fig. 3), so we argue that the GeV photons cannot be effectively produced from some parts of the original emitting region. The TPC model assumes high-energy photons are emitted along all the last open field lines with uniform emissivity extending from the stellar surface to high altitudes with $r_{\rm max} \sim R_{\rm lc}$. However, in the former outer-gap model, the inner boundary of the gap is the null charge surface where the pair creation process is significant (Zhang & Cheng 1997, 1998; Cheng et al. 2000). Furthermore, detailed electro-dynamical studies show that the inner boundary can be greatly shifted from the null surface to the star surface with the current through the gap taken into account (Hirotani & Shibata 2001a; Takata, Shibata & Hirotani 2004). The pair creation process is sensitive to the gap geometry which is still not known accurately (Tang et al. 2008), and the characteristics of the current across the gap in 3-dimensional geometry are still unclear. As a result, we propose that the high-energy photons cannot be effectively produced in the region corresponding to the distance of the null charge surface to the star for the last open field lines $r_{\rm in} > R_{\rm lc}$, and, for simplicity, we exclude the direct contribution from these field lines to the resulting light curve.

The panel (b) of Figure 4 shows the resulting light curve which simply excludes the emission from the field lines with $r_{\rm in} > R_{\rm lc}$ for the same parameters as Figure 3, and the azimuthal extension of the emission region is $\sim 245°$ (see panel (a) of Fig. 4). In this case, because the emission from some field lines corresponding to $r_{\rm in} > R_{\rm lc}$ is excluded, the amplitude of the bump in the bridge and the emission outside the two peaks are reduced. The model result underestimates the emission in the bridge region of $\Phi = 0.15 - 0.3$. As argued in Abdo et al. (2009), the emission in this region may come from the synchrotron emission from the relatively low-altitude pair cascades initiating the few-GeV curvature photons, and the model should not be used to tackle the profile in the region of $\Phi = 0.15 - 0.3$, although the notch following P1 can also be interpreted with it. The result shows that nearly zero flux can be produced from the magnetosphere of the pulsar in the off-pulse phase, and the resulting profile of the light curve is more consistent with the *Fermi* observation.

4 CONCLUSIONS AND DISCUSSION

Motivated by the new observations with the *Fermi* LAT in the GeV band on the Vela pulsar, we restudy the properties of the high-energy curve of pulsars with the TPC model proposed by Dyks & Rudak (2003) and Dyks et al. (2004). The model assumes that high-energy photons are emitted tangentially to the magnetic field lines around the last open field region, and the emission emerges from the star's surface to high altitudes with uniform emissivity. Prominent peaks in the light curves of pulsars can be produced due to caustic effects: the aberration of photon emission direction and the time delays are caused by the finite speed of light. The characteristics of the two dominating peaks in high-energy light curves of pulsars can be reproduced with the model, and each of the two peaks corresponds to a different magnetic pole.

The assumption of uniform emissivity of the high-energy photons determines that the model cannot be applied to both higher-energy photons with energy above several GeV, because they are easily attenuated in the magnetosphere, and those with lower energy of about several tens of MeV, since their emissivity changes greatly at different positions. Therefore, we apply the model to produce the light curve observed by the *Fermi* LAT in the energy band 0.3 – 1 GeV. The results show that the observed flux pattern of the two peaks and the bridge emission between them in the band of 0.3 – 1 GeV can be reproduced with the model. However, the resulting flux outside the two peaks is much higher than the observed one. This also indicates that more physical processes should be included in the model, such as the attenuation of high-energy photons and the details of the emission region. These may not emerge from the star's surface for some field lines, but are high above the cap like in the outer gap model (e.g., Tang et al. 2008). The TPC model assumes the high-energy photons are emitted near the last open field line region with uniform emissivity along the lines extending from the star's surface to high altitudes ($\sim R_{\rm lc}$). Motivated by the outer-gap model (e.g., Cheng et al. 2000), in which the inner boundary of the gap is the null charge surface where the production of pairs is significant, we propose a prescription that the high-energy photons cannot be effectively produced in the region corresponding to $r_{\rm in} > R_{\rm lc}$. Furthermore, the inner boundary can extend to the stellar surface if the current, which is either injected through the boundaries or produced in the gap, is taken into account. Since the pair production process is sensitive in the gap and the outer current across the gap for a pulsar is usually unclear, we simply exclude the emission from the field lines corresponding to $r_{\rm in} > R_{\rm lc}$ for simplicity. The result shows that the amplitude of the light curve outside the two peaks is greatly reduced, which is more consistent with the observation from LAT. Therefore, we argue that, unlike the TPC model, the high-energy photons cannot be effectively produced from the field lines for which the distance of the null point is relatively high above the light cylinder.

Acknowledgements We thank the anonymous referee for the suggestions to improve this paper. This work is partially supported by the National Natural Science Foundation of China (NSFC; Grant Nos. 10778702 and 10803005) and a 973 Program (2009CB824800).

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