Three-dimensional Two-Layer Outer Gap Model: *Fermi* Energy Dependent Light Curves of the Vela Pulsar

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Abstract: We extend the two-dimensional two-layer outer gap model to a three-dimensional geometry and use it to study the high-energy emission of the Vela pulsar. We apply this three dimensional two-layer model to the Vela pulsar and compare the model light curves, the phase-averaged spectrum and the phase-resolved spectra with the recent Fermi observations, which also reveals the existence of the third peak between two main peaks. The phase position of the third peak moves with the photon energy, which cannot be explained by the geometry of magnetic field structure and the caustic effects of the photon propagation. We suggest that the existence of the third peak and its energy dependent movement results from the azimuthal structure of the outer gap.

The Three Dimensional Gap:

- In this model, the outer gap is divided into two parts:

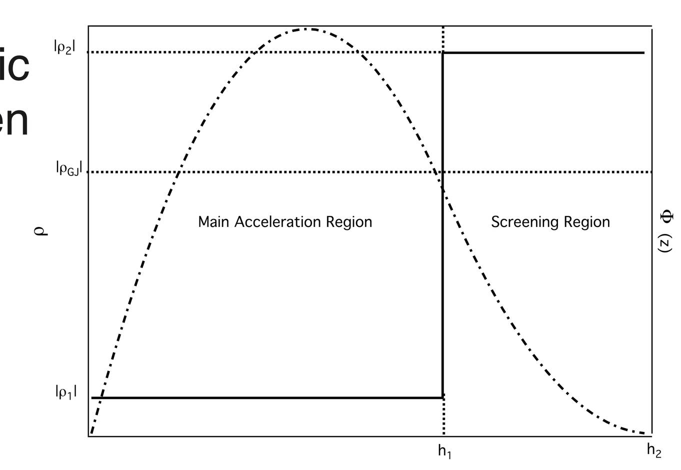
1) the main acceleration region on the top of last open field lines, where the charge density is much lower than the Goldreich-Julian charge density and the charged particles are accelerated by the electric field along the magnetic field to emit multi-GeV photons.
2) the screening region around the upper boundary of the gap, where the charge density is larger than the Goldreich-Julian value to close the gap and particles in this region are responsible for multi-100MeV photon emission.

- We use a simple step function to approximate the distribution of the charge density in the trans-field direction in the poloidal plane (the plane where the field lines have same polar angle).

- We adopt the rotating vacuum dipole field to calculate the light curves and spectra. The curvature photons are assumed to be emitted in the direction of the particle motion, which can be described as $\vec{v} = v_p\vec{B}/B + \vec{r}\times\vec{\Omega}$ (Takata et al. 2007)

- We introduce the factor a to represent the magnetic field lines at a given layer and take a = 1 for the last open field lines. For Vela Pulsar, we choose a=1 to 0.935.

- We divide the gap into many equal divisions in the azimuthal direction. The gap structure of each slice with a fixed azimuthal angle is approximately represented by the two-dimensional situation shown in Wang et al. (2010). Using the similar method, we solve the Poisson equation to obtain the potential and the accelerating electric field.



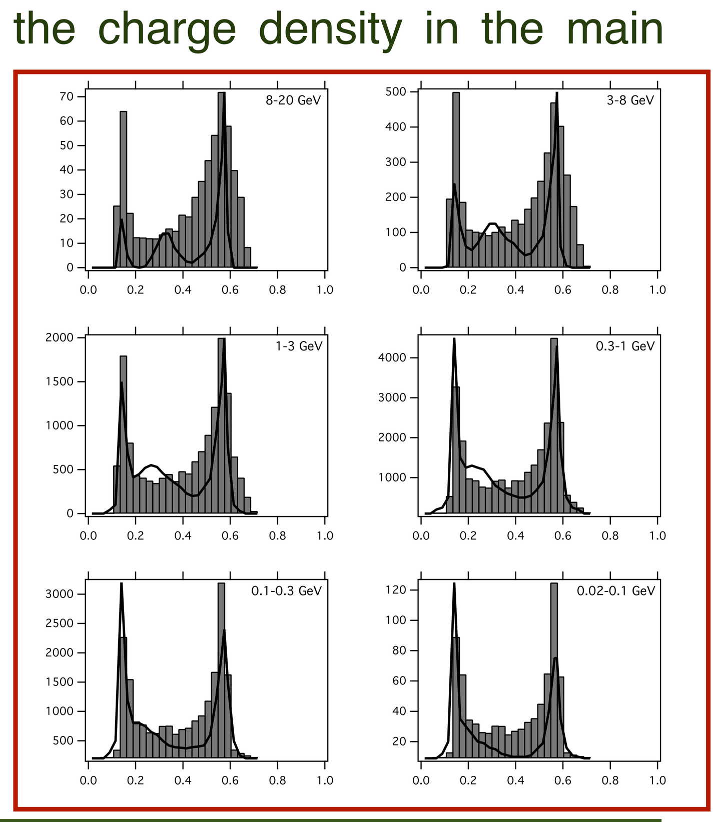
(The simplified distribution of the charge density (solid line) and the corresponding accelerating potential (dot-dashed line) of the two-layer outer gap.)

- The accelerated particles release the power gained from the accelerating electric field, through the curvature radiation process. As the case of the two-dimensional model, the shape of the spectrum is determined by gap fraction, f, the ratio of the size of main acceleration region to that of the whole gap, $\frac{h_1}{h_2}$, and the charge density in the main acceleration region, ρ_1.

The Simple Case:

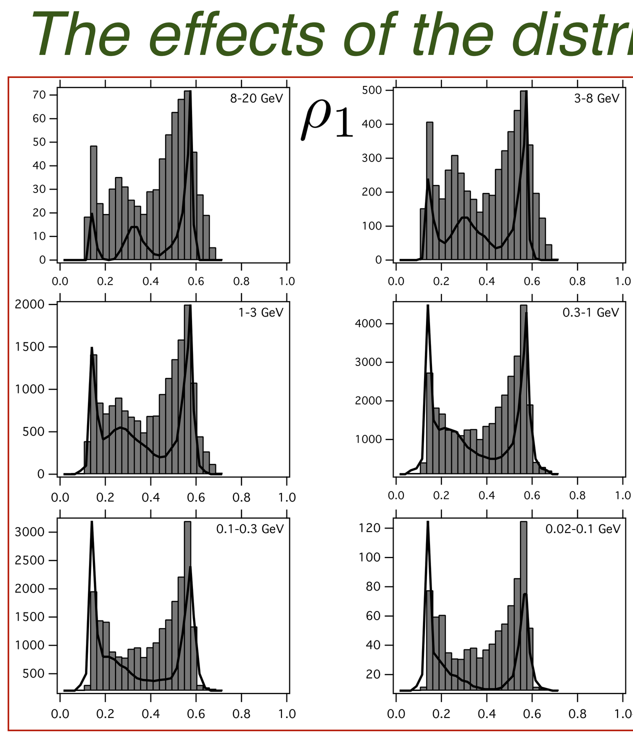
Firstly, we assume constant rho_1, h1/h2 and f in the azimuthal direction. rho_1 = 0.05, h1/h2 = 0.927 and f = 0.2.

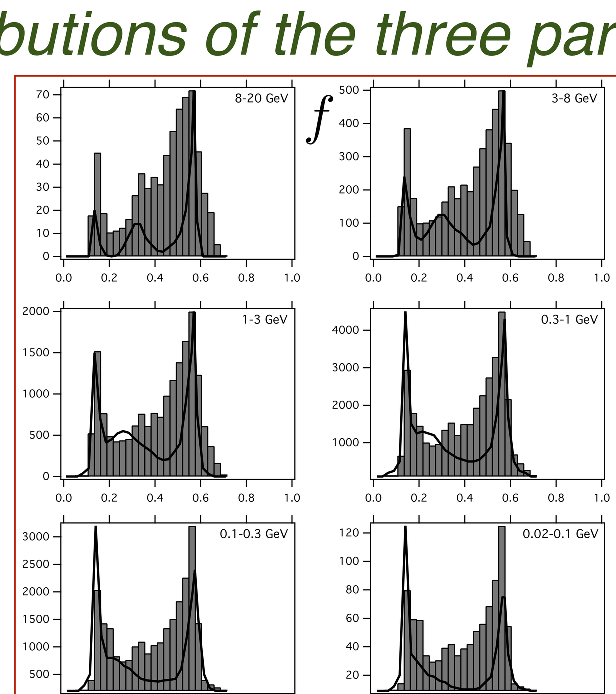
The simple caustic model can not explain the phase shift of the observed third peak. On these ground, we speculate that the existence of the third peak and its phase shift is related with more complex structure of the gap.

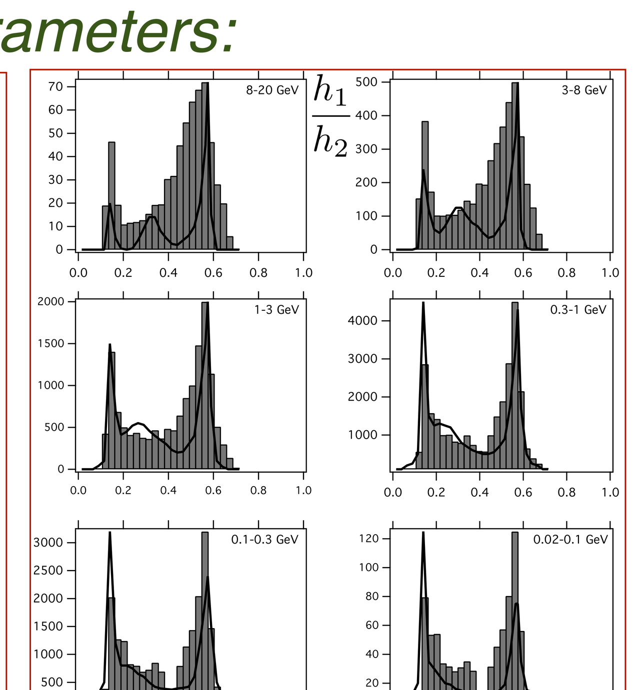


The solid lines are the observed light curves from Fermi-LAT (Abdo et al., 2010).

The effects of the distributions of the three parameters:

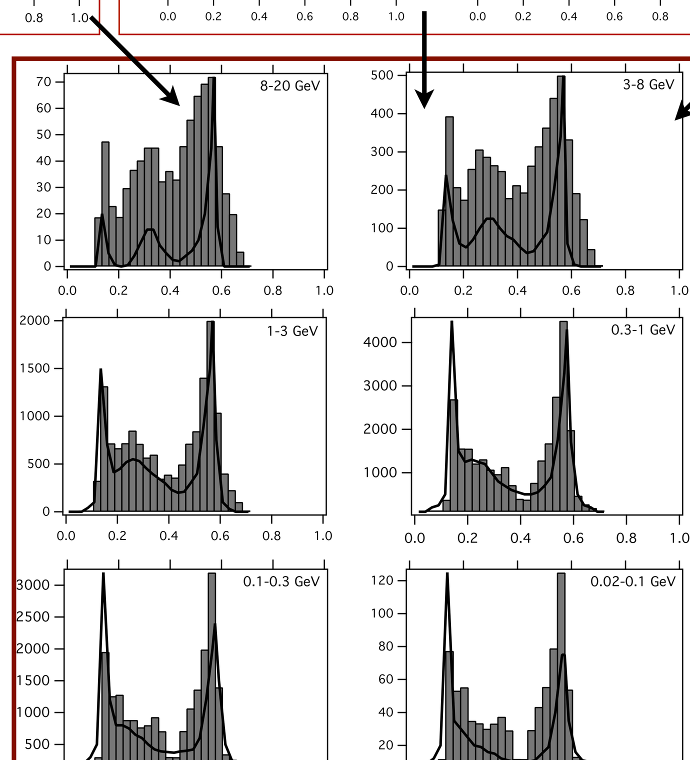


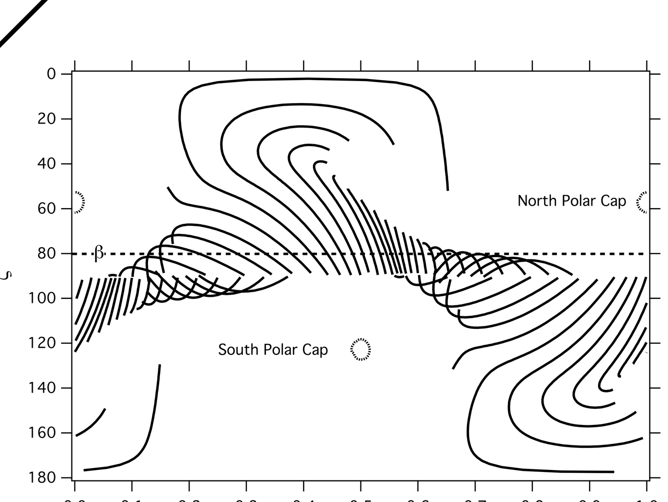




We let one of the three parameters to be a Gaussian function of the polar anlge and the other two as constant, to show how this parameter affects the shapes of the energy dependent light curves.

Then we combine the three together.





The skymap of the radiations outside of the null charge surface with inclination angle α = 57○. The x-axis is the pulse phase and the y-axis is the direction of the radiation. The dashed line is the viewing angle, which is chosen as β = 80○.

More Realistic Case:

- By the definition of the gap fraction of equation, we may choose the form of the azimuthal distribution of f.

$$f(\phi_p) = \frac{C}{r_p(\phi_p)}$$

- It is expected that as the null charge surface is closer to the stellar surface, the number density of the X-ray photons increases in the gap and therefore the screening region becomes thinner.

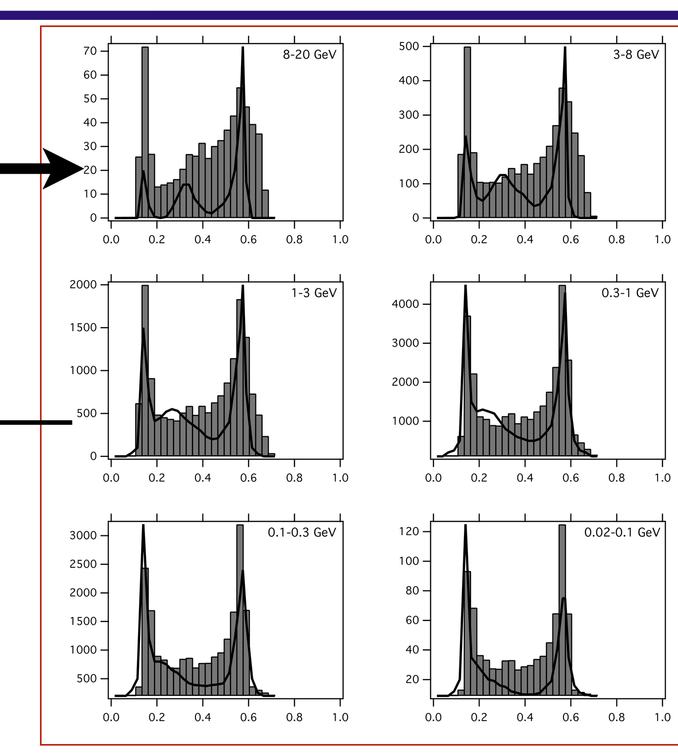
$$\frac{h_1}{h_2}(\phi_p) = B_1 + B_2\frac{1/r_{null}(\phi_p) - 1/r_{null}^{max}}{1/r_{null}^{min} - 1/r_{null}^{max}}$$

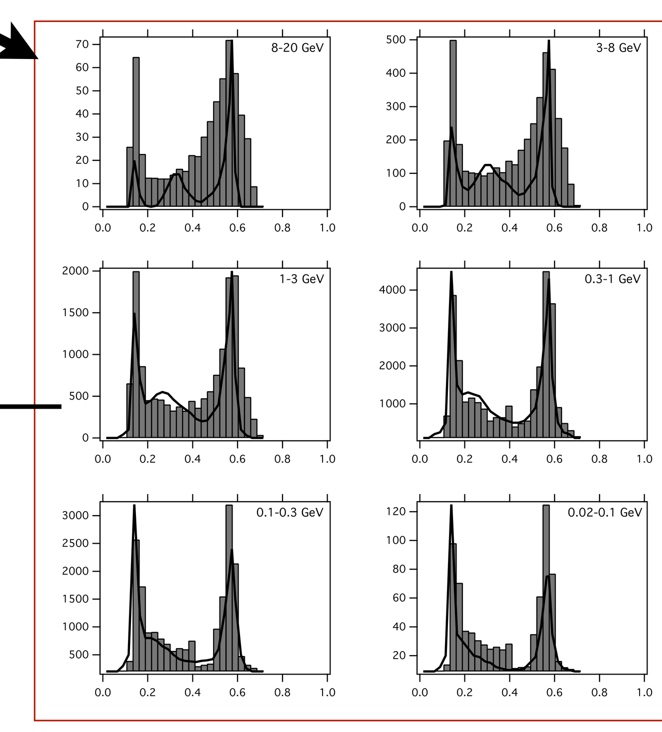
- We assume that the averaged charge density has a distribution in the azimuthal direction due to the effect of E⊥×B drift motion. Without the effect of drifting, the number of particle in ϕp-cell is $N_0(\phi_p) \propto f(\phi_p)\bar{\rho}_0(\phi_p)$. With the drifting effect, the real number of particle in ϕ_p cell (N(ϕp)) may come from $(\phi_p + \Delta\phi_p)$ cell, $N(\phi_p) = N_0(\phi_p + \Delta\phi_p)$

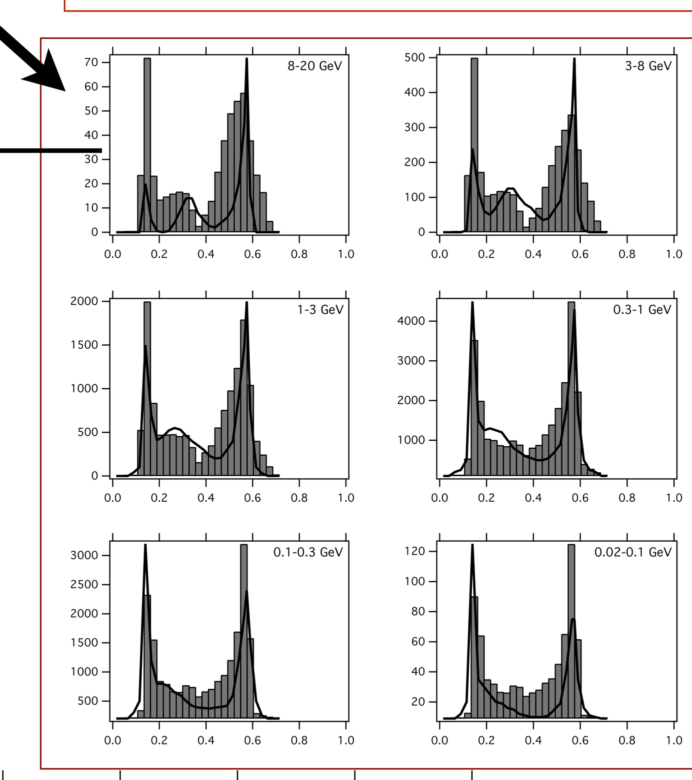
Since the average charge density, $\bar{\rho}(\phi_p) = N(\phi_p)/f(\phi_p)$ we obtain:

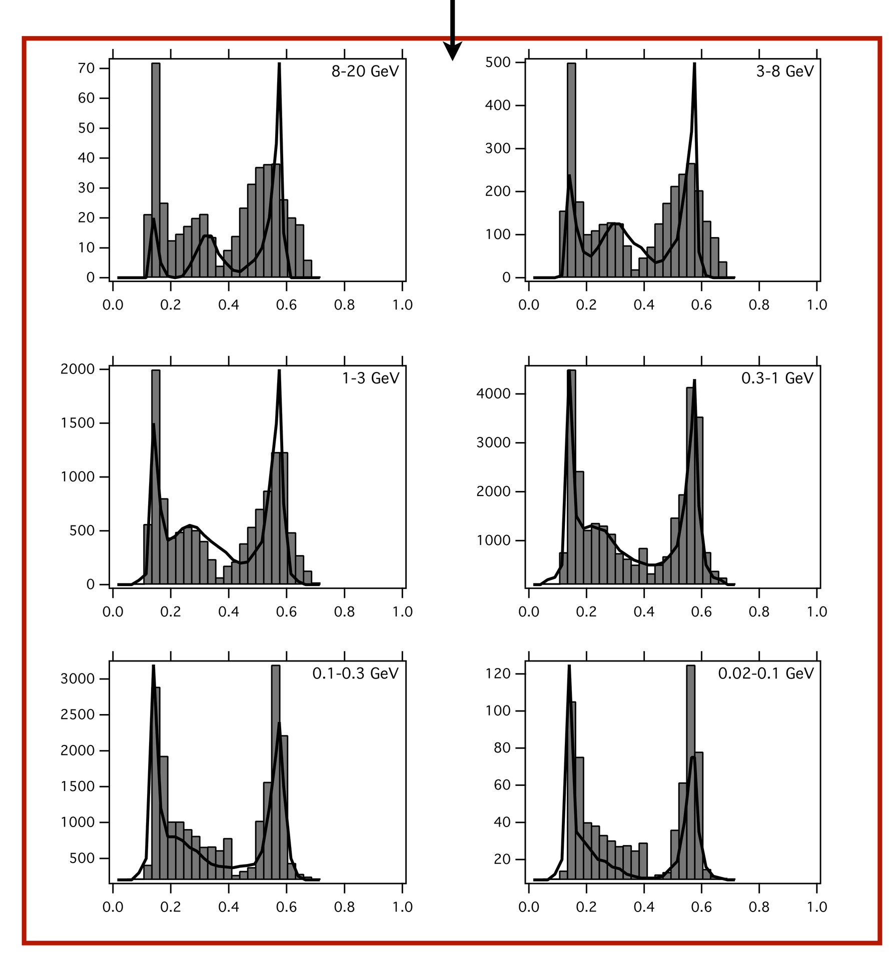
$$\bar{\rho}(\phi_p) = \bar{\rho}_0\frac{f(\phi_p + \Delta\phi_p)}{f(\phi_p)} \qquad \bar{\rho}_0 \sim 0.5$$

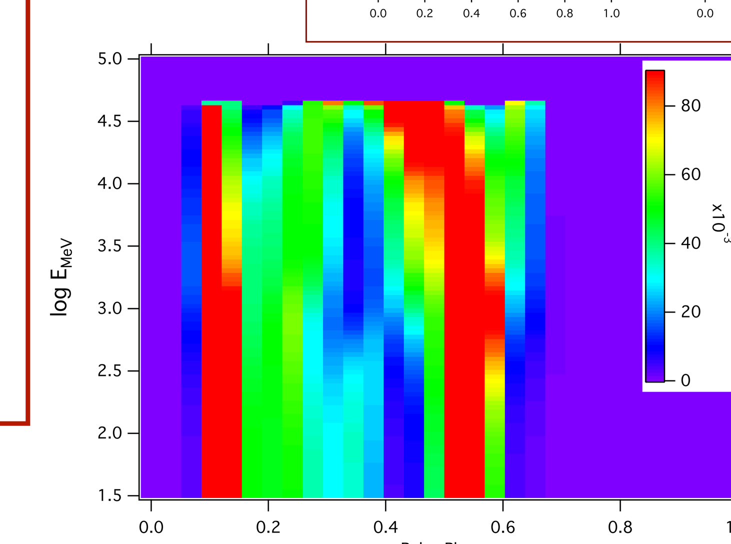
$$\Delta\phi_p = -28^\circ\frac{1/r_{null}(\phi_p) - 1/r_{null}^{max}}{1/r_{null}^{min} - 1/r_{null}^{max}}$$





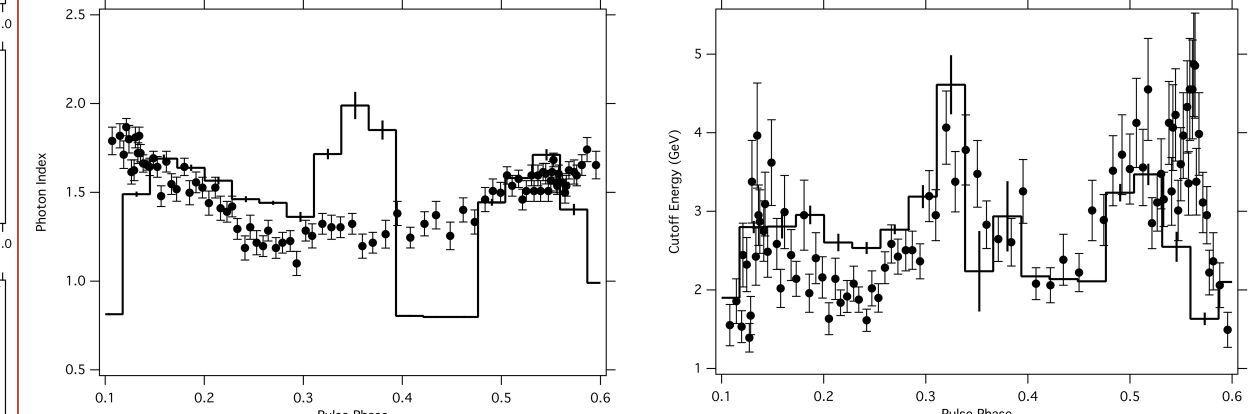




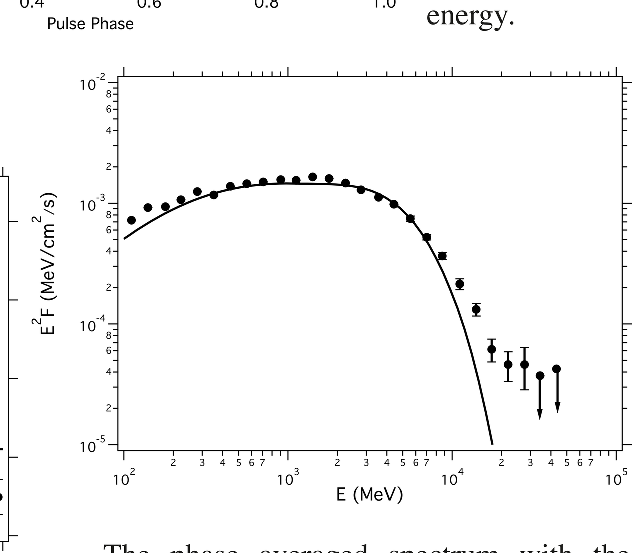


Intensity map in the pulse phase and energy plane. The darkness represents the percentage of the number of the photons of certain interval of pulse phase in the total number of photons of certain interval of energy.

We also show that the present model can reproduce the distribution of the cut-off energy for each rotation phase.



The photon indices and cut-off energies of the phase-resolved spectra of different pulse phases given by the more realistic model, comparing with the observed data (circle) (Abdo et al., 2010).



The phase averaged spectrum with the distributions of rho_1, h1/h2 and f, comparing with the observed data (circle) from Fermi-LAT (Abdo et al., 2010)

Conclusion:

We find that the distributions of rho_1 and f make third-peak-like structure in the bridge region of light curve above 1 GeV, while the distribution of h1/h2 makes a bump in the bridge region of the light curves below 1 GeV. The phases of the third peaks caused by the azimuthal distributions of h1/h2, rho_1 and f are different from each other. Consequently, the difference in the phases produces the shift of the combined third peak with the photon energy.

References:

Abdo A.A. et al., 2010, ApJ, 713, 154

Takata J., Chang H.-K. & Cheng K.S., 2007, ApJ, 656,1044

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