The Effect of Different Magnetospheric Structures on Predictions of Gamma-ray Pulsar Light Curves

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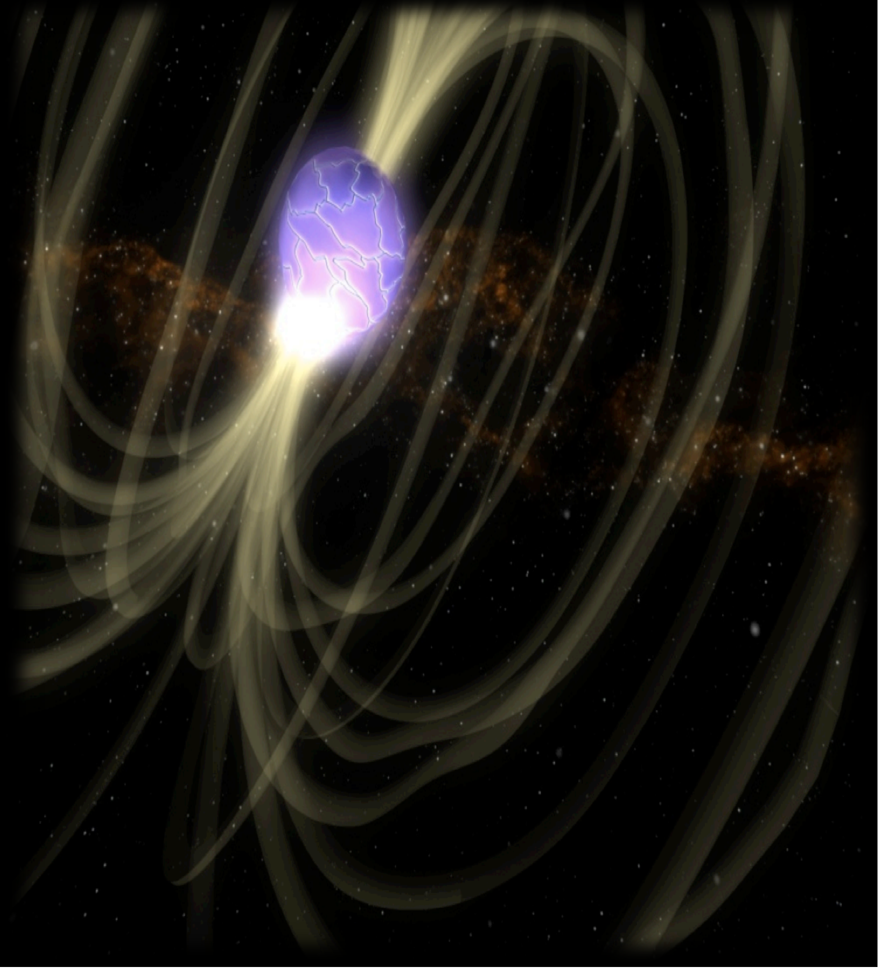
Introduction

- The first neutron star (NS) was discovered in 1967 by Jocelyn Bell from Cambridge (Chaisson, 2002).

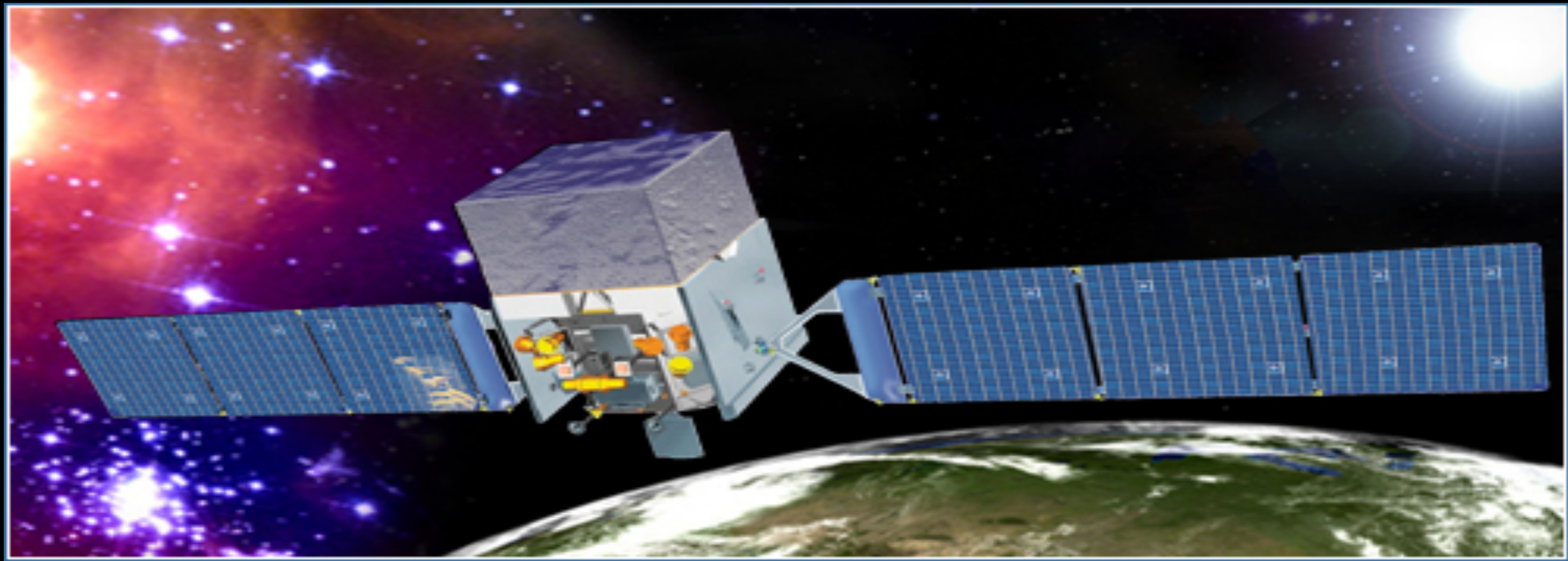
- Compact, highly magnetized NSs, rotating at tremendous rates

- Emits radiation across the electromagnetic spectrum.

- Focus on γ-ray pulsars



Fermi LAT



- γ-ray telescope with a field of view of 2.4 steradians (sr) enabling it to observe 20% of the sky in a time frame of a few hours .

- Measures γ-ray pulsars in energy range of 20 MeV to 300 GeV

- The second pulsar catalogue contain in excess of 100 γ-ray pulsars (Abdo 2012).

Geometric γ-ray pulsar models

Ω : rotation axis
μ : magnetic axis,
α : inclination angle (degrees),
ζ : observer angle (degrees)

How do the two models differ?
- Gap region (extent)

TPC (Dyks03):
- from stellar surface up to $\sim R_{\mathrm{LC}}$

OG (Romani96):
- above null charge surface up to $\sim R_{\mathrm{LC}}$;
- interior emission layer embedded inside gap

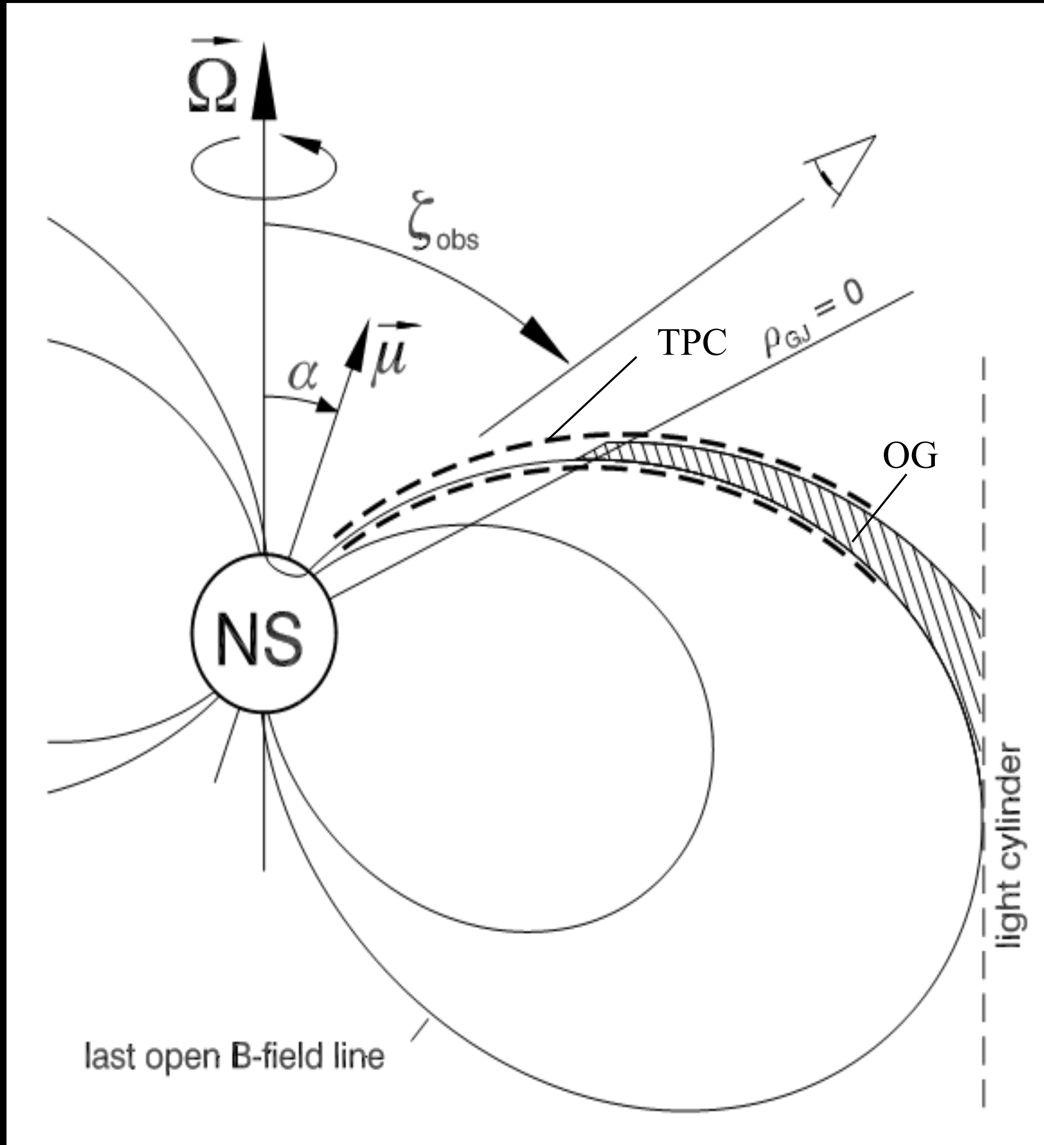


Fig 1: Geometric models of a NS (Dyks, 2003)

Magnetic fields

Static vacuum dipole field:

$$\mathbf{B}_{st} = \frac{\mu}{r^3}\left(2\cos\theta\hat{\mathbf{r}} + \sin\theta\hat{\boldsymbol{\theta}}\right) \quad 1$$

Retarded vacuum dipole field:

$$B_{ret,r} = \frac{2\mu}{r^3}[\cos\alpha\cos\theta + \sin\alpha\sin\theta(r_n\sin\lambda + \cos\lambda)] \quad 2a$$

$$B_{ret,\varphi} = -\frac{\mu}{r^3}\sin\alpha\,[(r_n^2 - 1)\sin\lambda + r_n\cos\lambda] \quad 2b$$

$$B_{ret,\theta} = \frac{\mu}{r^3}\{\cos\alpha\sin\theta + \sin\alpha\cos\theta\,[-r_n\sin\lambda + (r_n^2 - 1)\cos\lambda]\} \quad 2c$$

With $r_n = \frac{r}{R_{LC}}$, r the radial distance and $\lambda = r_n + \varphi - \Omega t$.
By setting r_n and α equal to zero the retarded vacuum dipole reduces to the static dipole case.

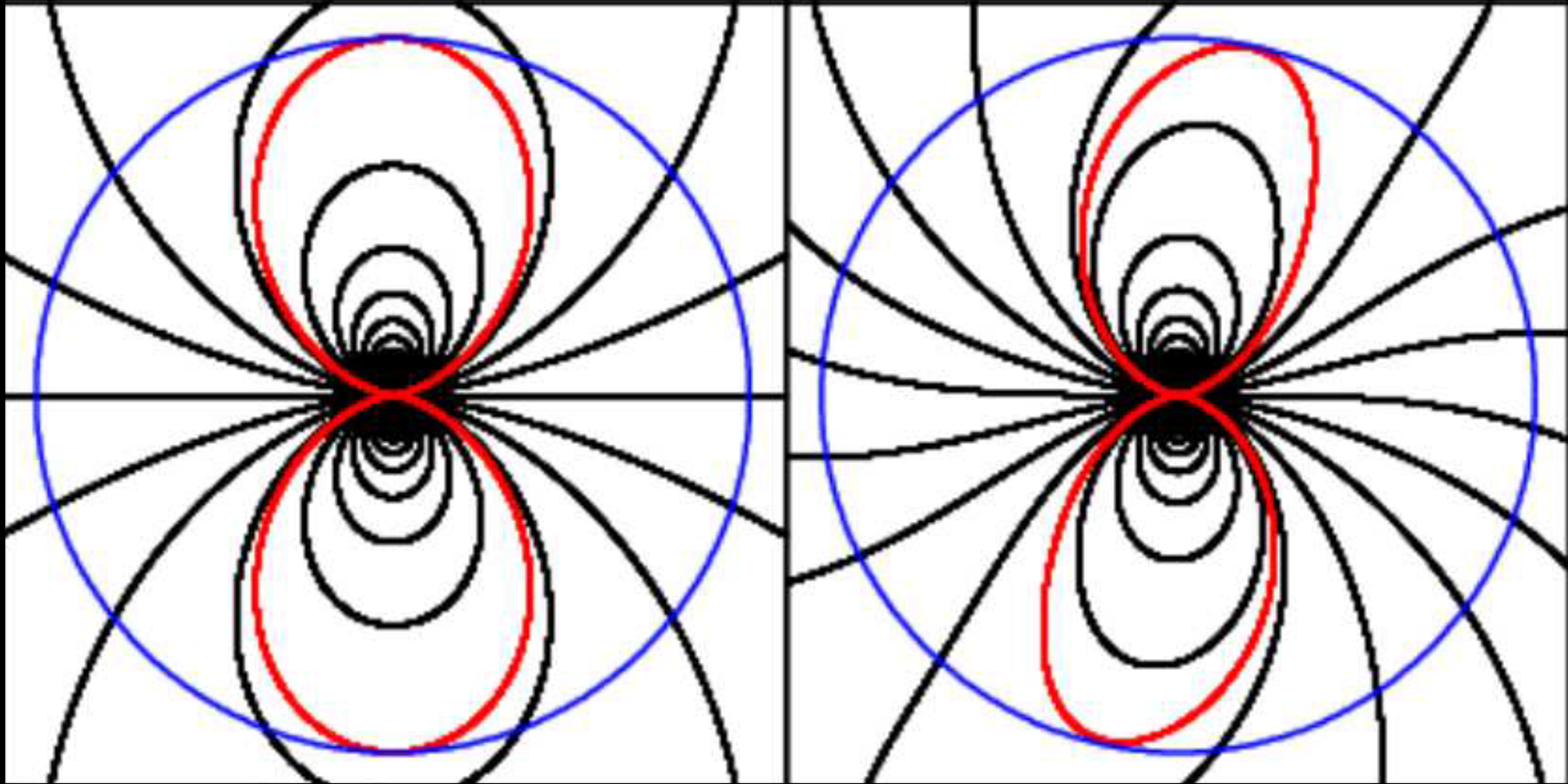


Fig 2: On the left the static vacuum dipole and on the right the retarded vacuum dipole (Roger, Romani & Watters, 2010)

Problem statement

- Different B-field solutions, including the static vacuum dipole and the retarded vacuum dipole, are implemented in an existing geometric modelling code.

- The standard emission geometries assumed two-pole caustic (TPC) and outer gap (OG) models.

- We studied the impact of different magnetospheric structures on the predictions of gamma-ray pulsar LCs

- As an application, we compared our model LCs with *Fermi* LAT data for the Vela pulsar, and inferred the most probable configuration in this case.

Method

- Used an existing geometric modelling code (Dyks 2004).

- 4 combinations of 2 B-field structures:
  1. Static vacuum dipole
  2. Retarded vacuum dipole

  and 2 geometric models:

  3. TPC
  4. OG

- Construct sky maps and LCs for different α and ζ, using a 5° resolution.

- Sky maps: intensity per solid angle, and a function of φ and ζ with φ the phase angle.

- LCs a function of φ and ζ, i.e. constant ζ-cut through sky maps.

(Chi)^2 – method (statistical method)

-χ^2 a function of α and ζ.

-Lower model LCs resolution so that both model and data have the same amount of bins.

-Smooth the data using a Gaussian Kernel Density Estimator (KDE).

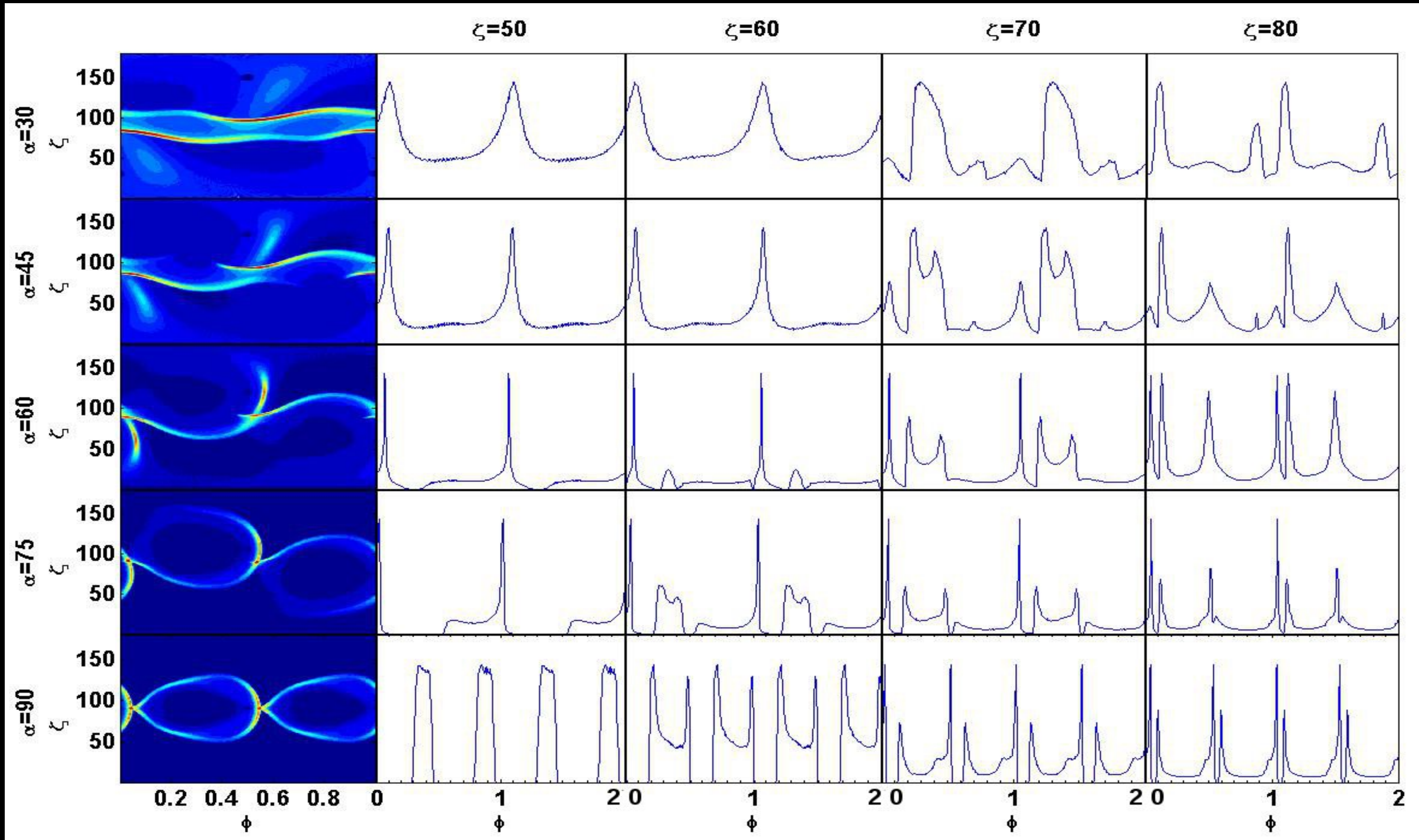
-Data treated as being cyclic.

-Aligned maximum peaks of model and data before calculating χ^2 (α, ζ).

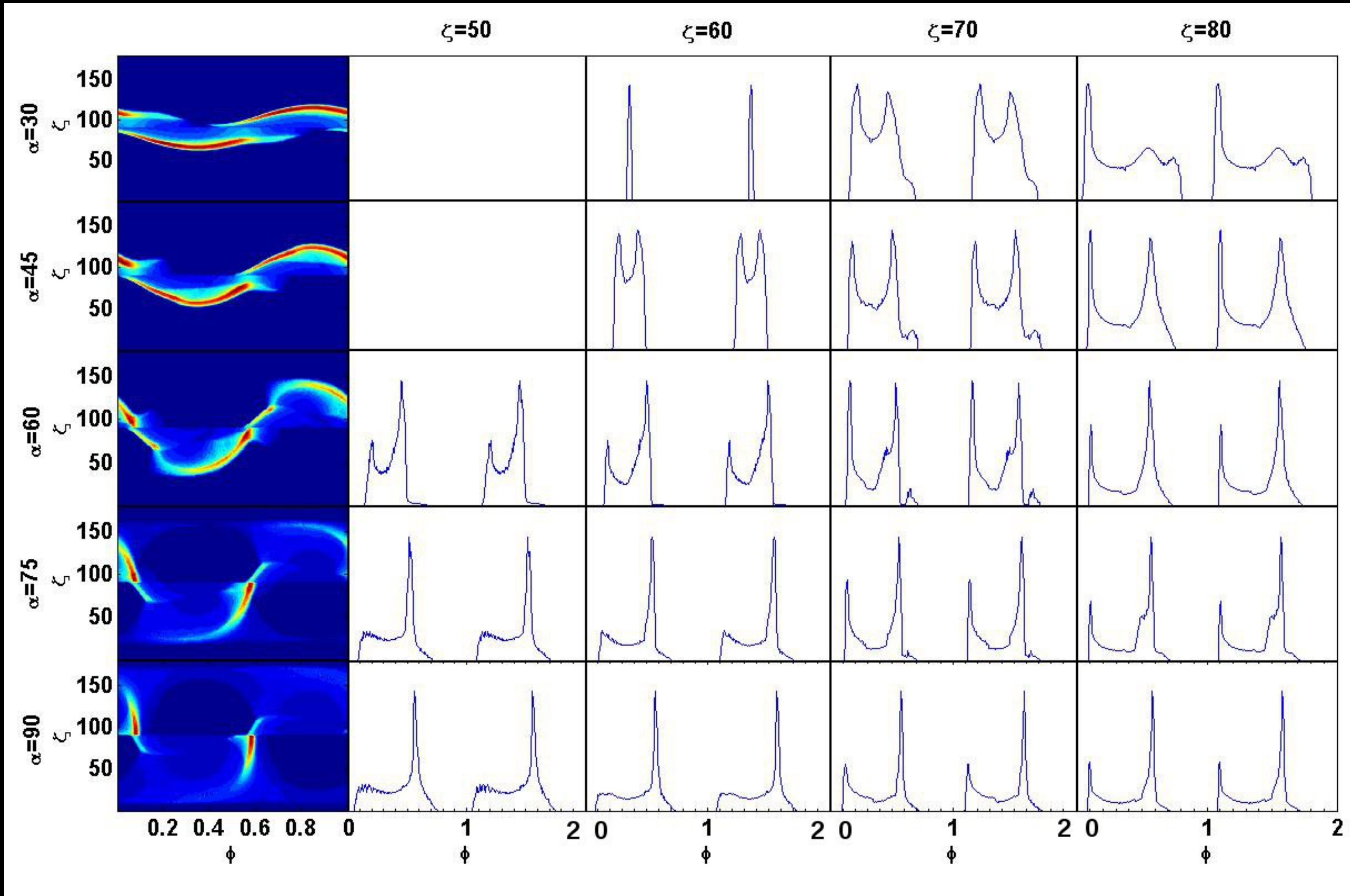
-Construct contour plots for χ^2, indicating the best-fit solution.

Results

<u>Sky maps and LCs</u> (for different α and ζ) and $R_{max} = 1.2R_{LC}$ From TPC model using the static dipole field:

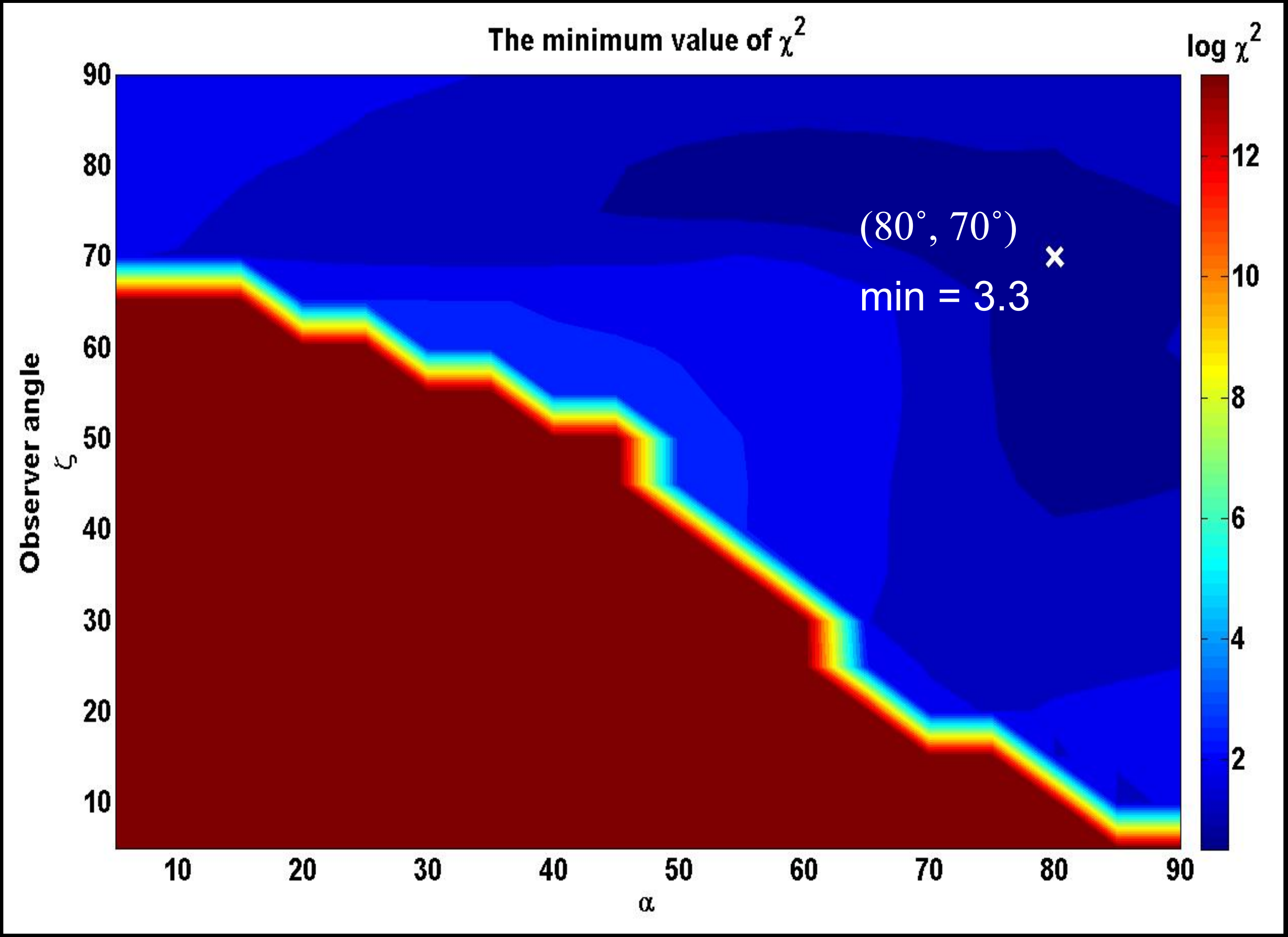


From OG model using the retarded dipole field:



Contour plot: χ^2 (α and ζ)

From OG model using the retarded dipole field:



<u>Best fit LC for Vela:</u> (φ and relative intensity)
From OG model using the retarded dipole field:

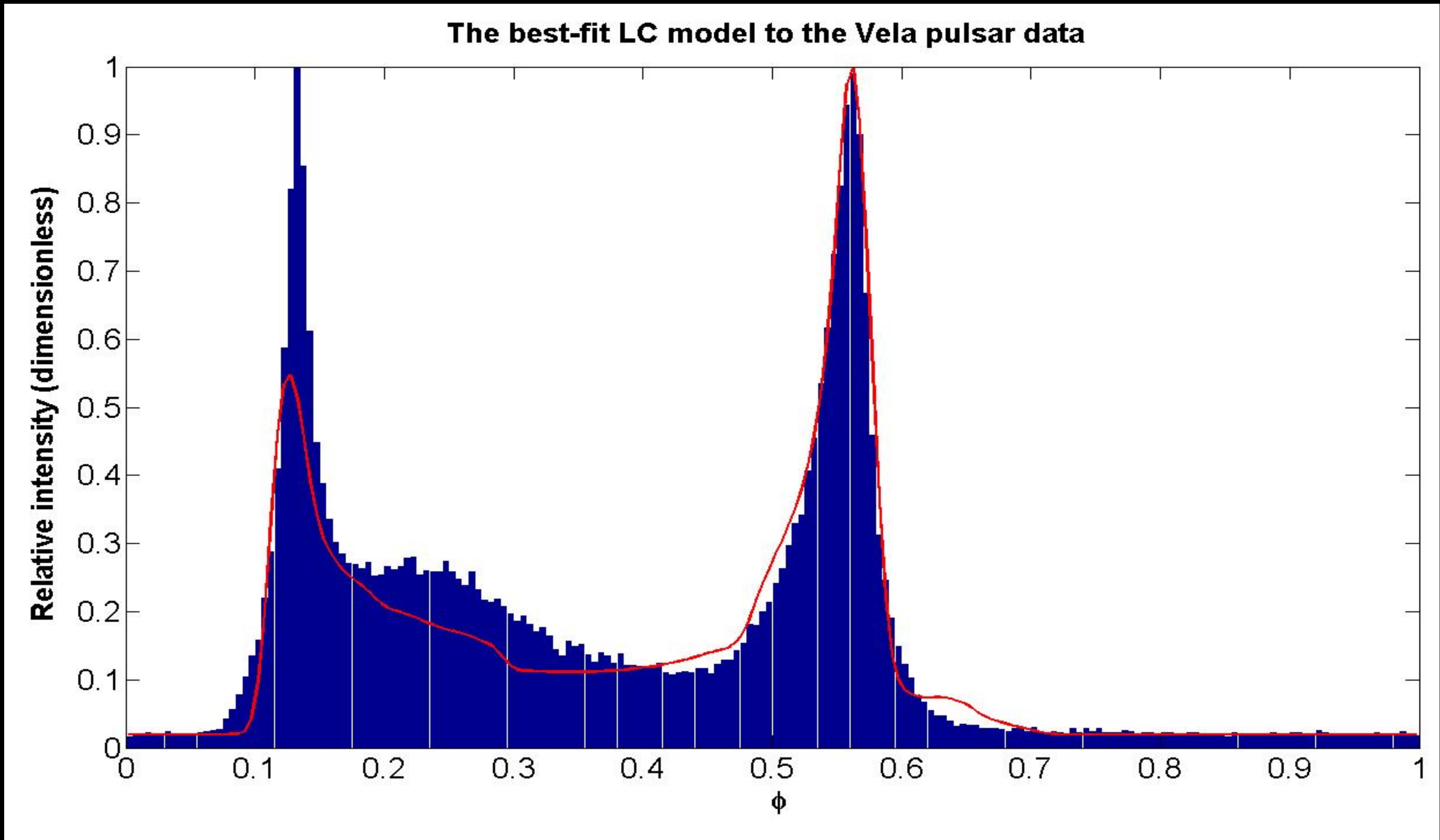


Table 1: Best-fit (α,ζ) for the Vela pulsar

		Our model		Reference fit (Watters 2009)	
Combination	**$\log_{10} \chi^2$**	**α (°)**	**ζ (°)**	**Vela α (°)**	**Vela ζ (°)**
Static dipole					
TPC	**15.3**	**60**	**85**		
OG	**6.4**	**65**	**85**		
Retarded dipole					
TPC	**15.7**	**70**	**55**	**62 - 68**	**64**
OG	**3.3**	**80**	**70**	**75**	**64**

Conclusions

It is evident that the magnetospheric structure and emission geometry determine the pulsar visibility and also the γ-ray pulse shape.

We applied our models to the Vela pulsar and found a best fit from the OG model using the retarded dipole field, for $(\alpha, \zeta) = (80^\circ, 70^\circ)$ with $\log_{10} \chi^2 = 3.3$. This is close to the value of $(\alpha, \zeta) = (75^\circ, 64^\circ)$ inferred by (Watters, 2009).

Future work

Implement additional magnetic field solutions:

- Offset dipole (Harding, 2011)
- Pair-starved dipole (Harding, 2005)

Study the effect of these additional solutions on the predicted pulsar LCs.

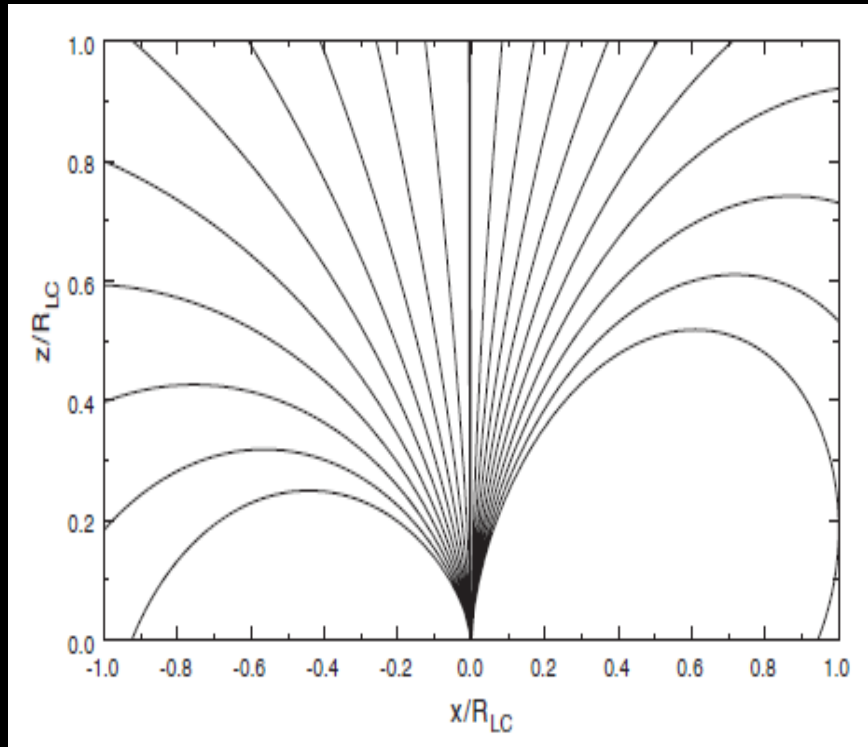


Fig 3: Offset dipole field in x-z plane with an offset parameter of ϵ=0.2

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"God's love and kindness will shine
upon us like the sun that rises in the sky."
Luke 1:73