Multi-wavelength emission region of γ-ray emitting pulsars

S. Kisaka & Y. Kojima

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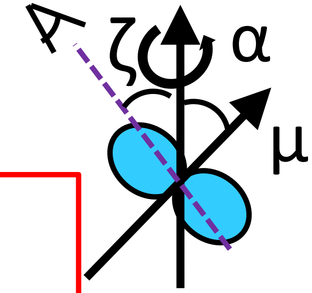
(Hiroshima University)

ABSTRACT

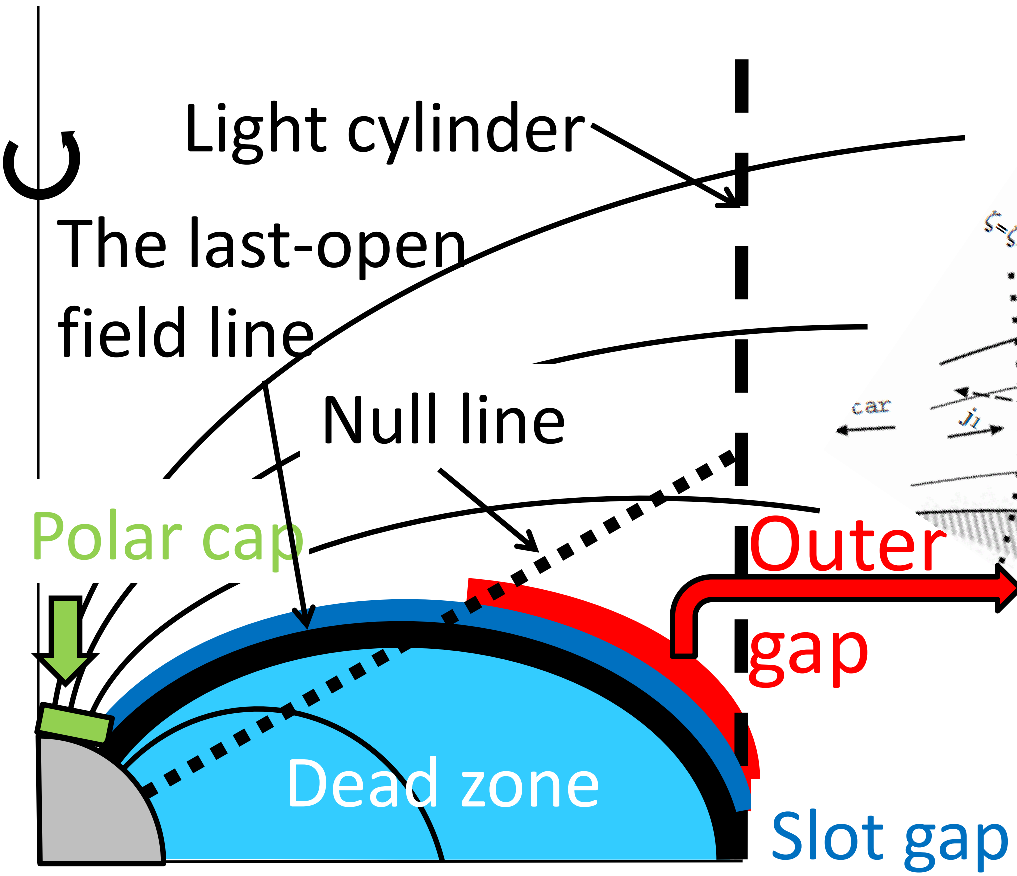
Recent observations by the Fermi Gamma-Ray Space Telescope of γ-ray pulsars have revealed further details of the structure of the emission region. Using the outer gap model, we investigate the emission region for the multi-wavelength light curve. We parameterize the altitude of the emission region. We find that the outer gap model can explain the multi-wavelength pulse behavior. We also find a general tendency for the altitude of the γ-ray emission region.

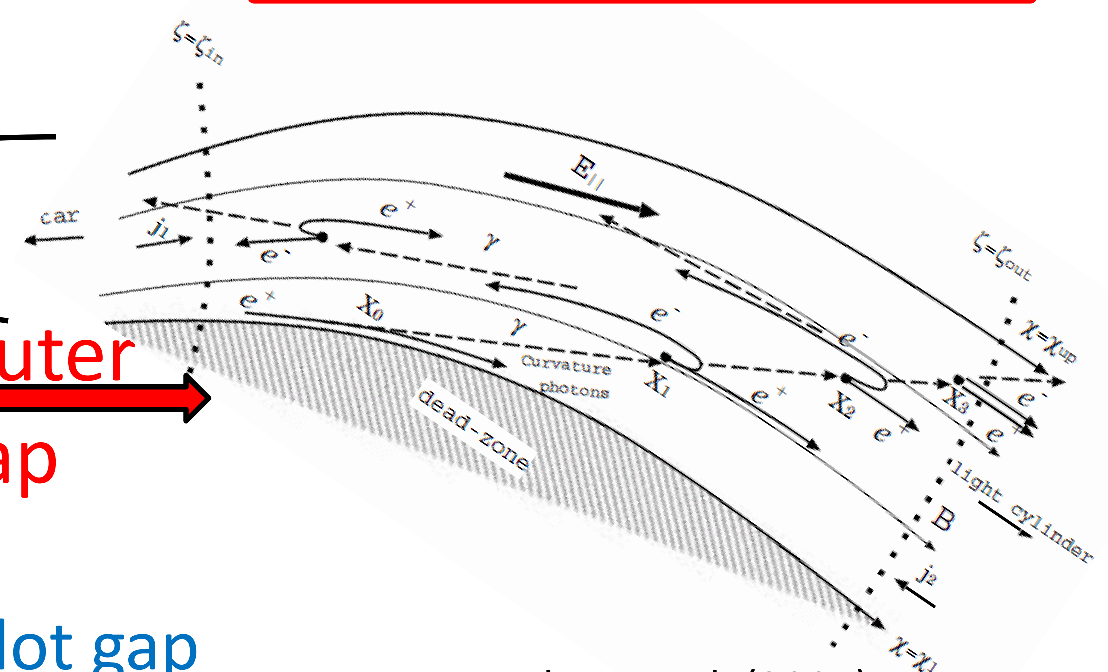
Emission model



Little is known about the high-energy emission region in the pulsar magnetosphere.

We focus on the outer gap model.

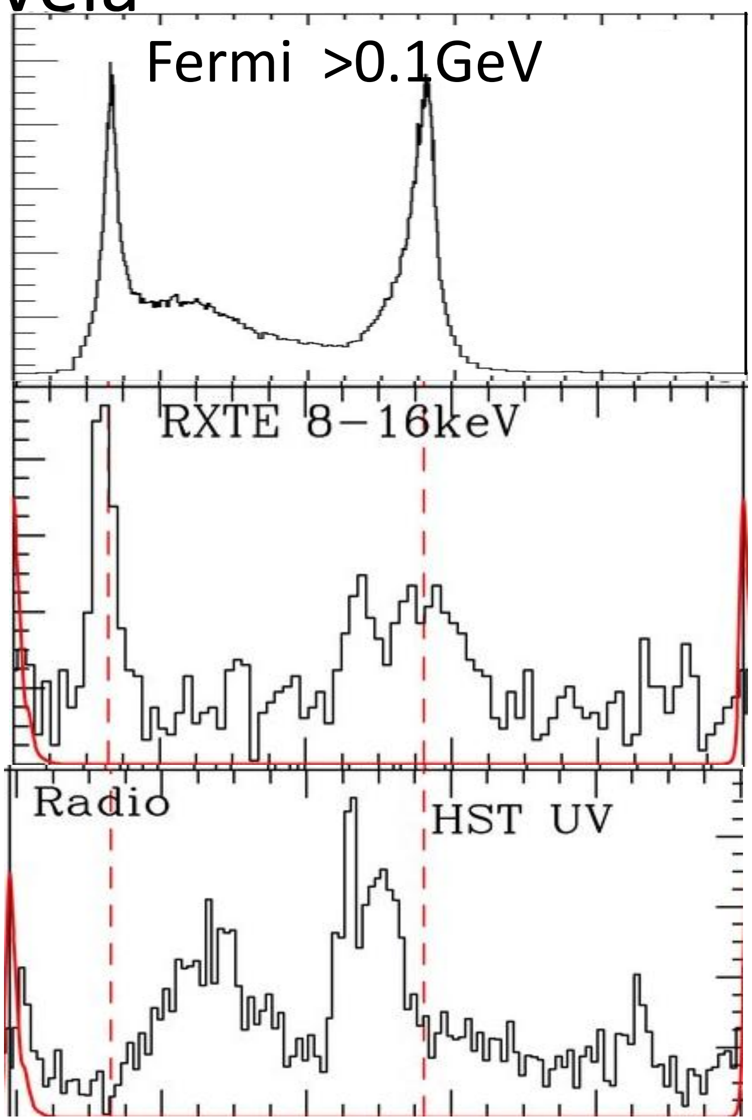


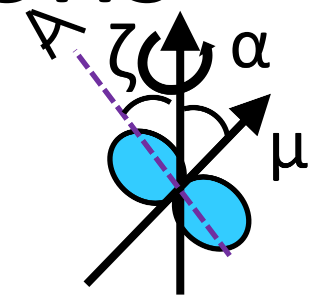


Takata et al. (2004)

Difference of peak positions

Vela

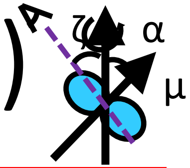




The position of the peaks depends on energy range. Since peaks are made by caustics in the outer gap model, emission in each band comes from different region.

Abdo et al. (2010) ApJ 706 1331
Abdo et al. (2009) ApJ 696 1084

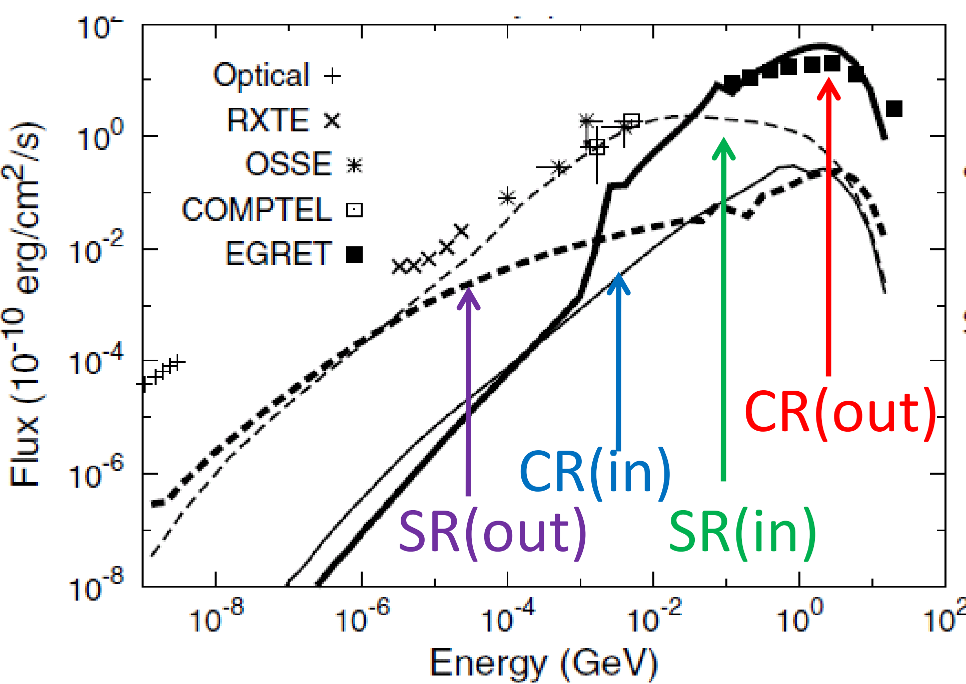
Outer gap model (Takata et al. 2008)

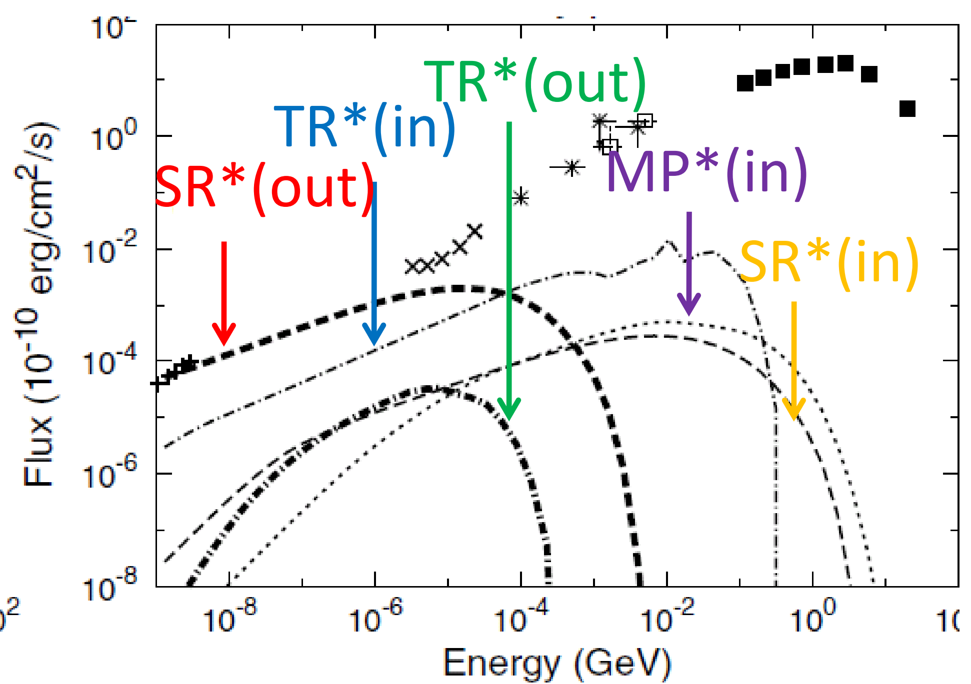


	Direction	Emission region
γ-ray :	Outward	Particle acceleration region
X-ray :	Outward & inward	Particle acceleration region
UV/opt.:	Outward & inward	Out of that region

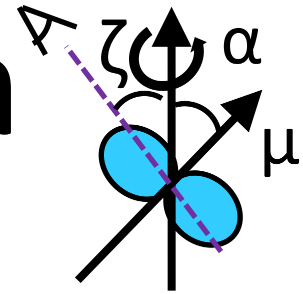
Emission from the particle acceleration region

Emission outside the particle acceleration region





Emission calculation



Assumptions

- Magnetic field : Rotating dipole
- Emission direction : Along the particle trajectory
- Emissivity : Constant
- Emission region : $r_{null} < r < R_{lc}$ (outer gap)

r_{null}: Radial distance to null surface
R_{lc} : Light cylinder radius

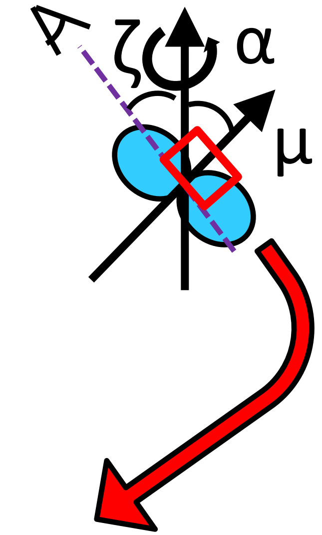
Parameters

- Magnetic colatitudes : $r_{ov} \equiv r_{pc}/r_{pc,0}$
- Inclination angle : α
- Viewing angle : ζ

We focus on the peak phases of the light curve.

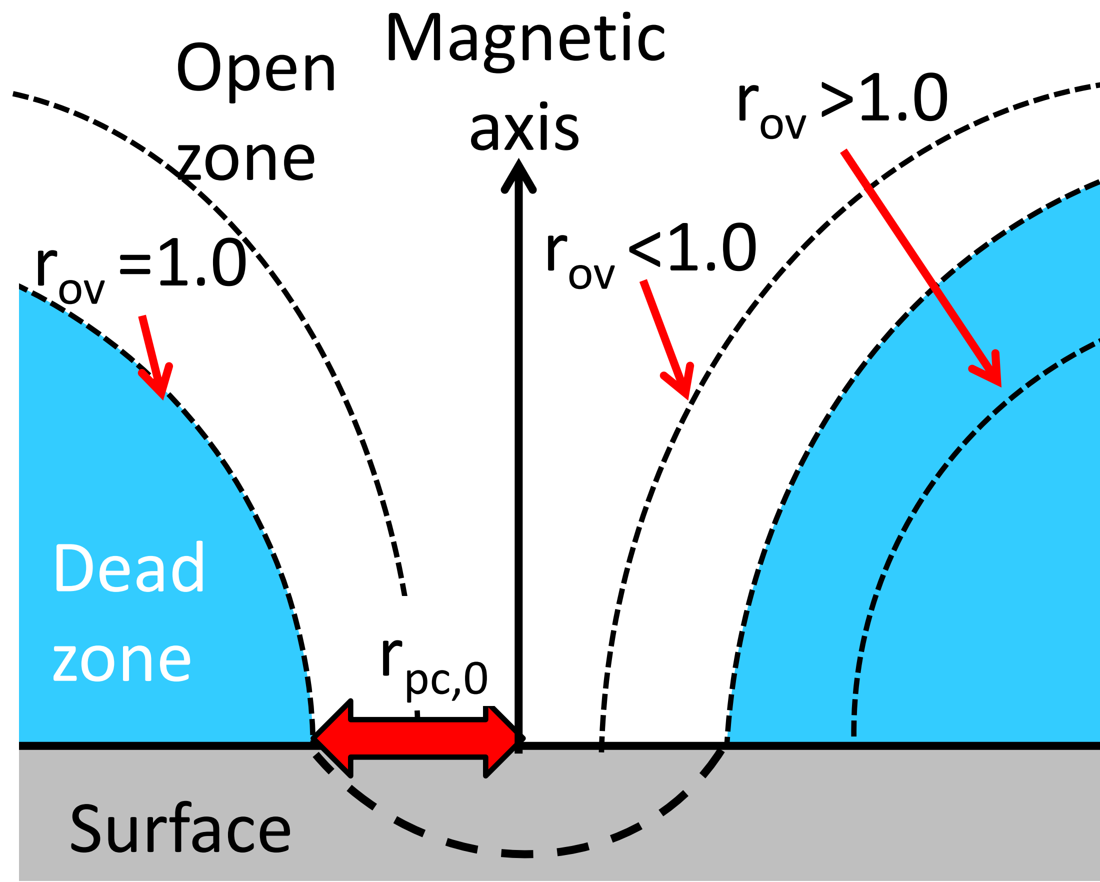
Parameters

- Magnetic colatitudes : $r_{ov} \Xi r_{pc}/r_{pc,0}$
- Inclination angle : α
- Viewing angle : ζ

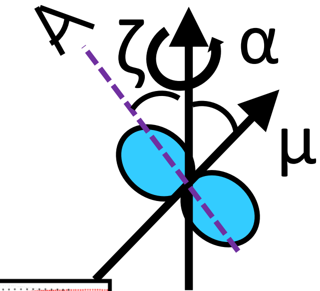


The parameter r_{ov} corresponds to the altitude of the emission region.

$r_{ov}=1.0$ the last-open line
$r_{ov}<1.0$ open zone
$r_{ov}>1.0$ dead zone

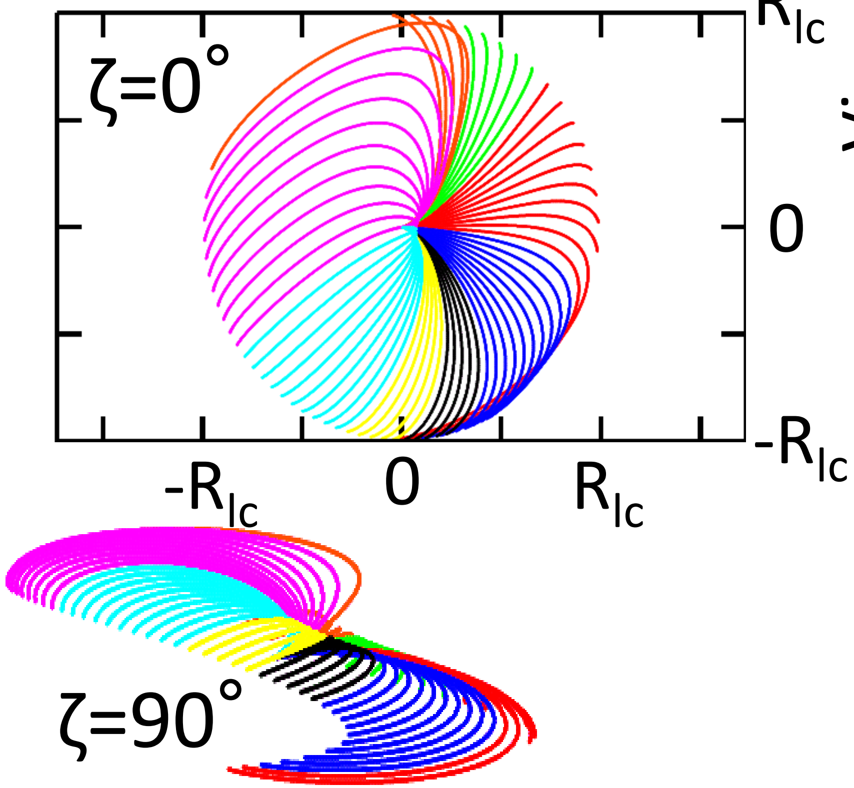


Example(1)

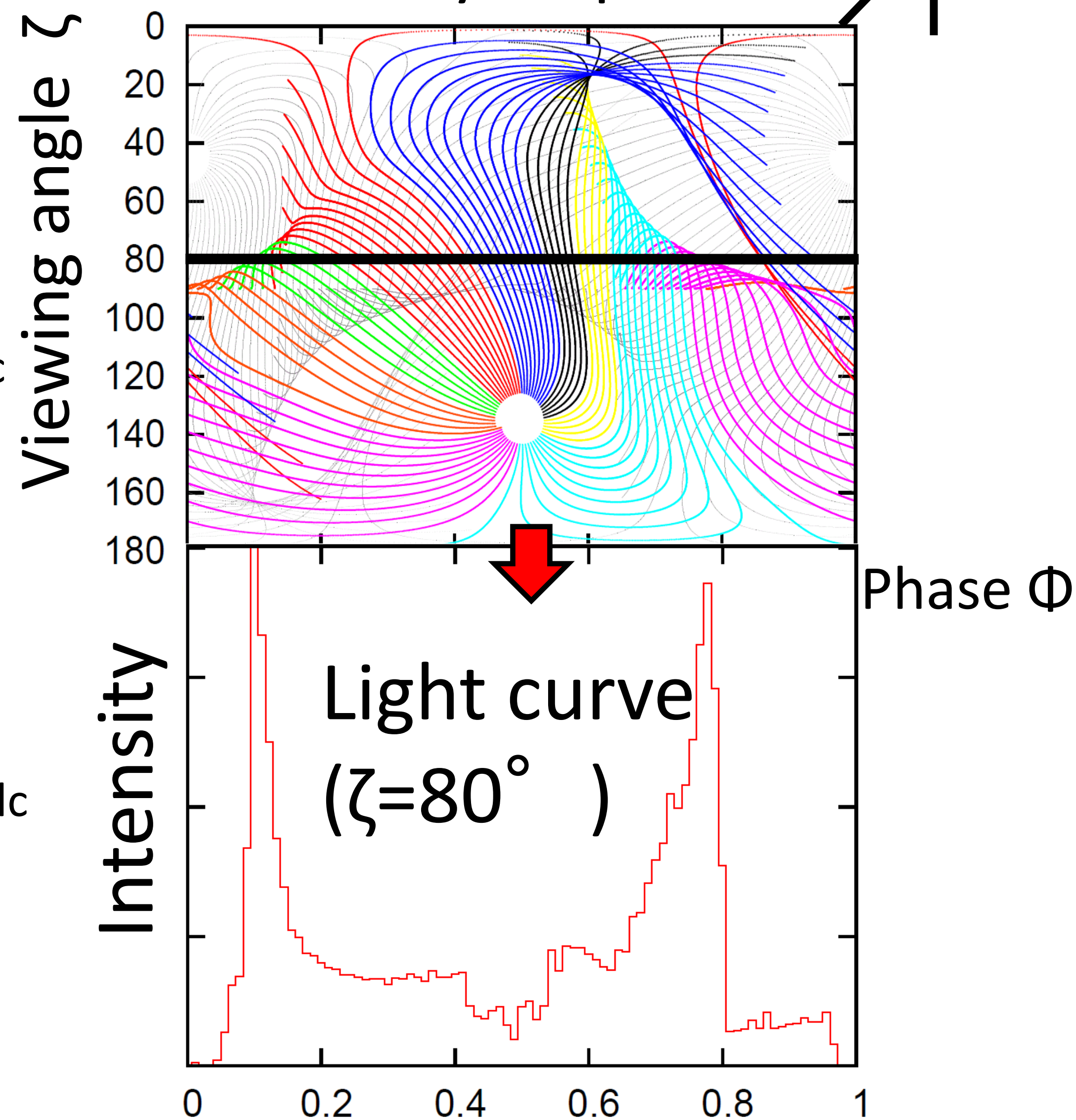


- Peak multiplicity
- Peak separation
- Radio lag

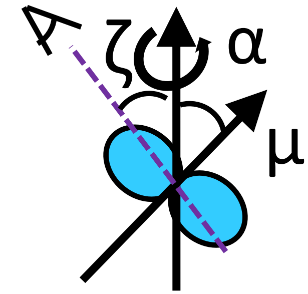
α=45°



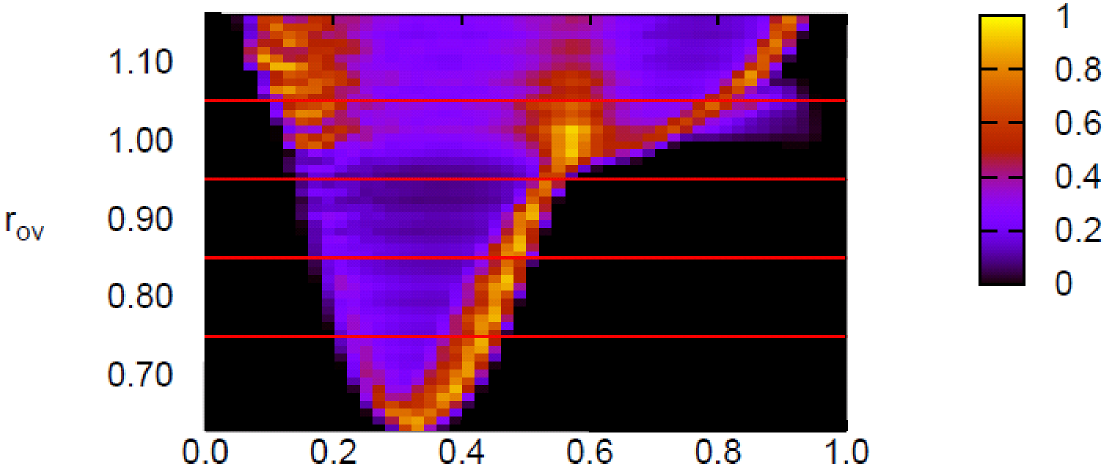
Sky map



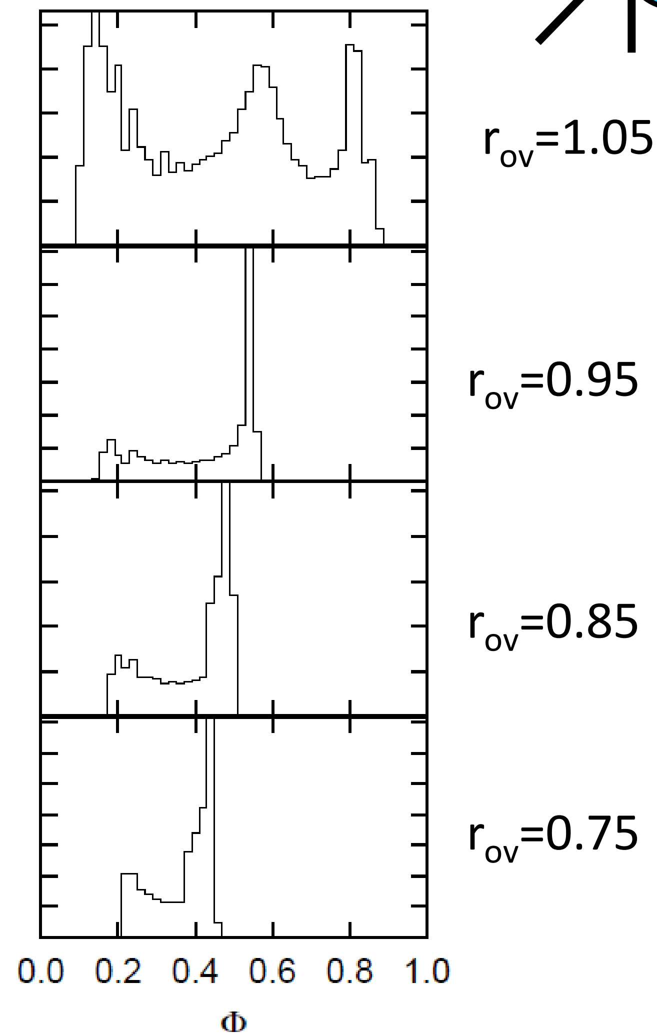
Example(2)



Dependence on r_{ov}
$(\alpha,\zeta)=(72, 64)$

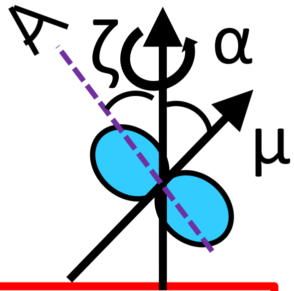


Phase Φ



At each altitude, we normalize the intensity by the maximum.

Samples



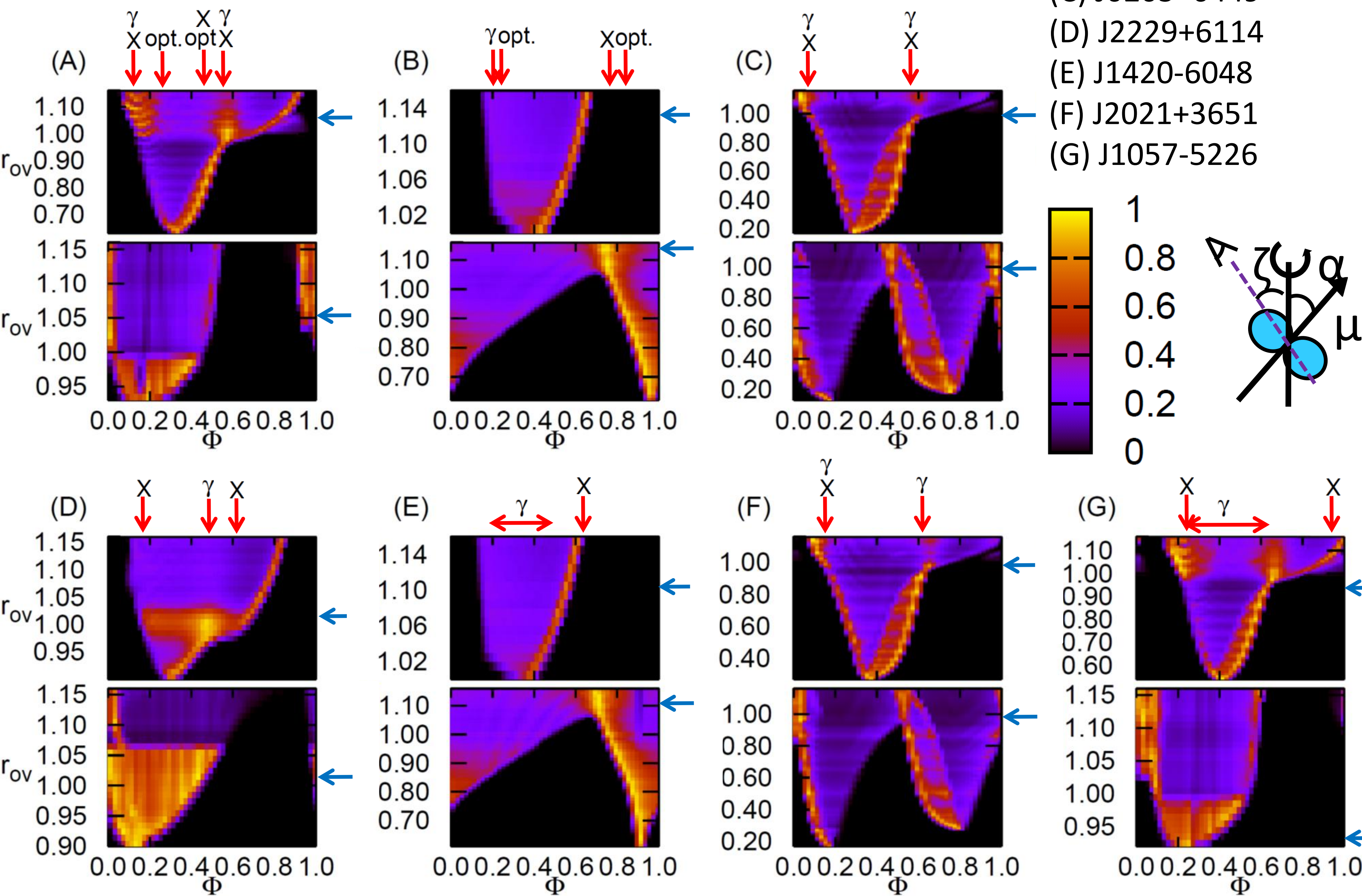
Selection criteria

- Non-thermal pulses are detected in addition to the γ-ray and radio bands.
- The geometrical parameters (α,ζ) are observationally constrained. (RVM, PWN fitting)

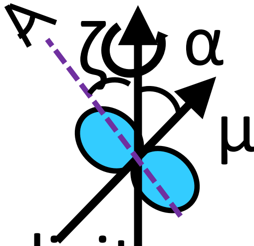
Name (1)	$\log(L_{SD})$ (erg s^{-1}) (2)	τ_c (kyr) (3)	$\log(B_s)$ (G) (4)	α (degrees) (5)	ξ (degrees) (6)
J0835-4510	36.84	11	12.53	72	64
J0659+1414	34.58	110	12.67	29	38
J0205+6449	37.43	5	12.56	78	88
J2229+6114	37.35	11	12.31	55	46
J1420-6048	37.00	13	12.38	30	35
J2021+3651	36.53	17	12.50	75	85
J1057-5226	34.48	540	12.03	75	69

Comparison to observations

(A) J0835-4510(Vela)
(B) J0659+1414
(C) J0205+6449
(D) J2229+6114
(E) J1420-6048
(F) J2021+3651
(G) J1057-5226



Mean free path



Since detectable γ-rays are radiated with large multiplicity by the pair plasma in the gap region, the mean free path of a -ray photon should be less than light cylinder radius.

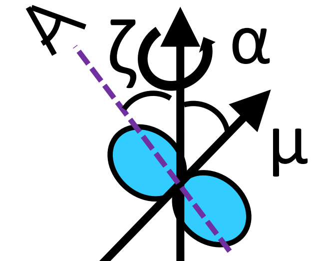
Mean free path $$\lambda(r) \approx 4.7 P^{13/21} (B_s / 10^{12} G)^{-2/7} r$$

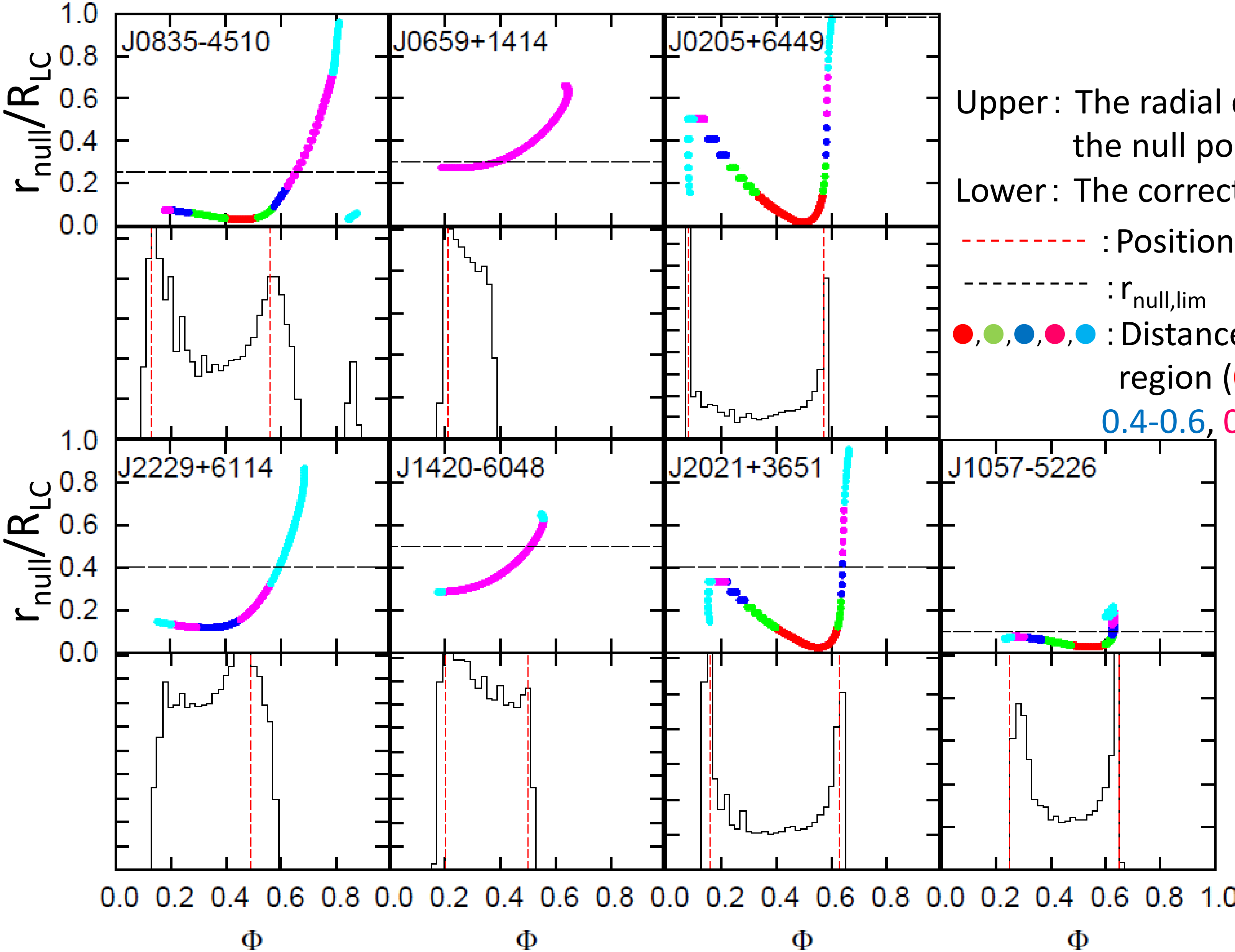
Zhang & Cheng (1997)

By taking into account the azimuthal extensions with $\lambda(r_{null}) < 0.2\text{-}0.7\ R_{lc}$, the fits of the resultant light curves become better.

Name	r_{ov}(γ-, X-ray)	r_{ov}(UV/optical)	$r_{n,lim}$ (R_{LC})	$\lambda(r_{n,lim})$ (R_{LC})
J0835-4510	1.05-1.06	0.65-0.80	0.25	0.23
J0659+1414	1.13-1.14	0.90-1.04	0.30	0.60
J0205+6449	0.97-0.98	...	1.00	0.71
J2229+6114	1.01-1.02	...	0.40	0.29
J1420-6048	1.10-1.11	...	0.50	0.42
J2021+3651	0.97-0.98	...	0.40	0.40
J1057-5226	0.93-0.94	...	0.10	0.20

γ-ray light curves





Upper : The radial distance to the null point

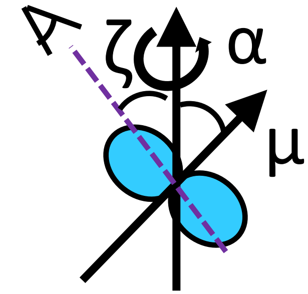
Lower : The corrected light curves

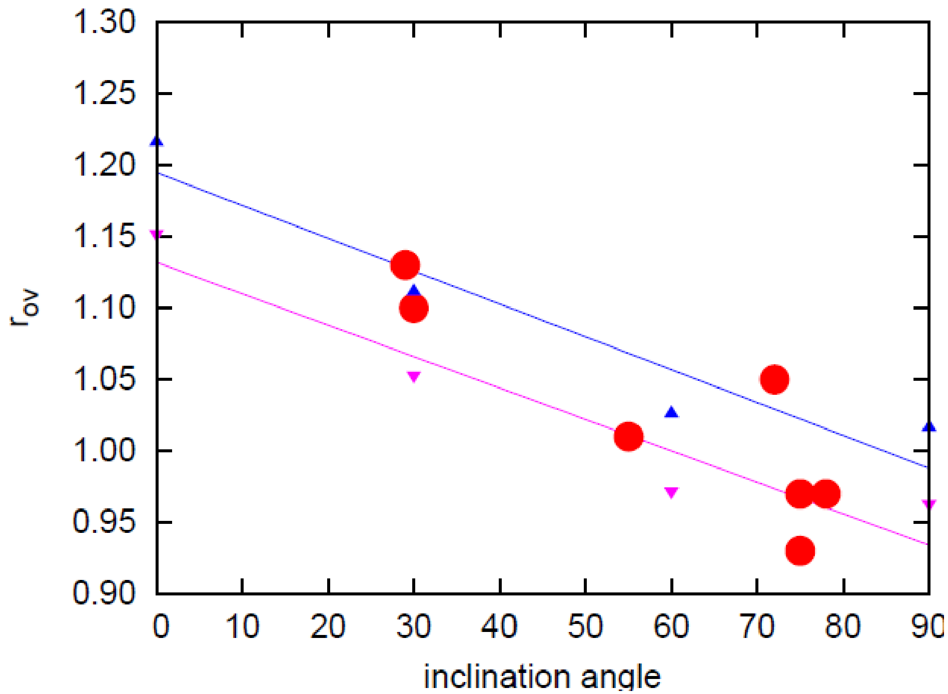
: Positions of γ-ray peak

: $r_{null,lim}$

●,●,●,●,● : Distance to emission region (0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1.0)

Statistical properties

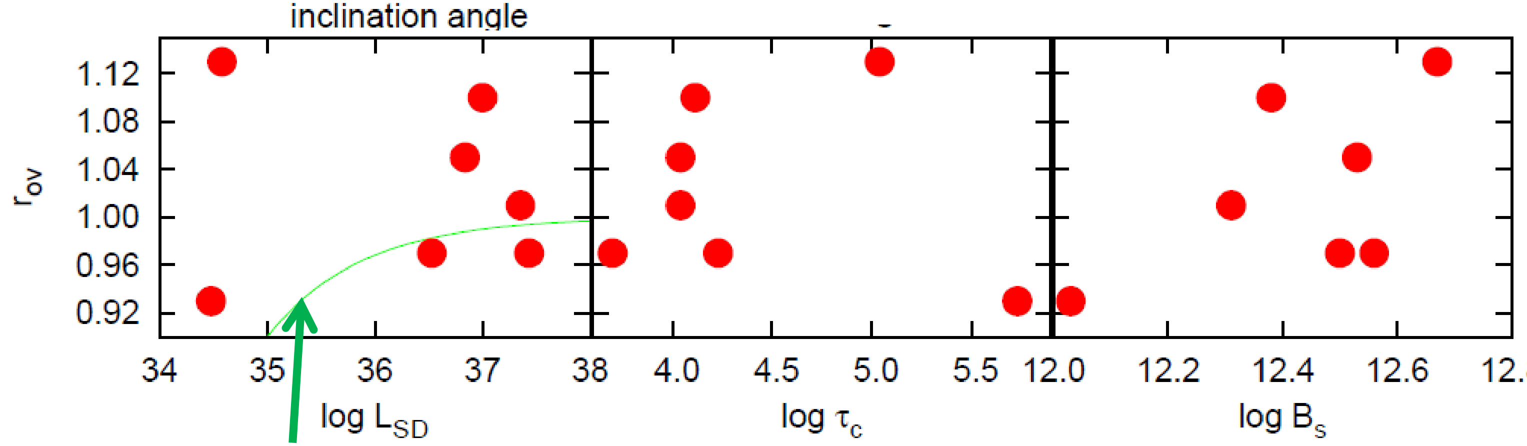




The altitude of the emission region is correlated with inclination angle. This relationship is very similar to the separatrix layer in a force-free magnetosphere.

▼, ▲: separatrix layer

($r_{ov,ff}$=0.90, 0.95)

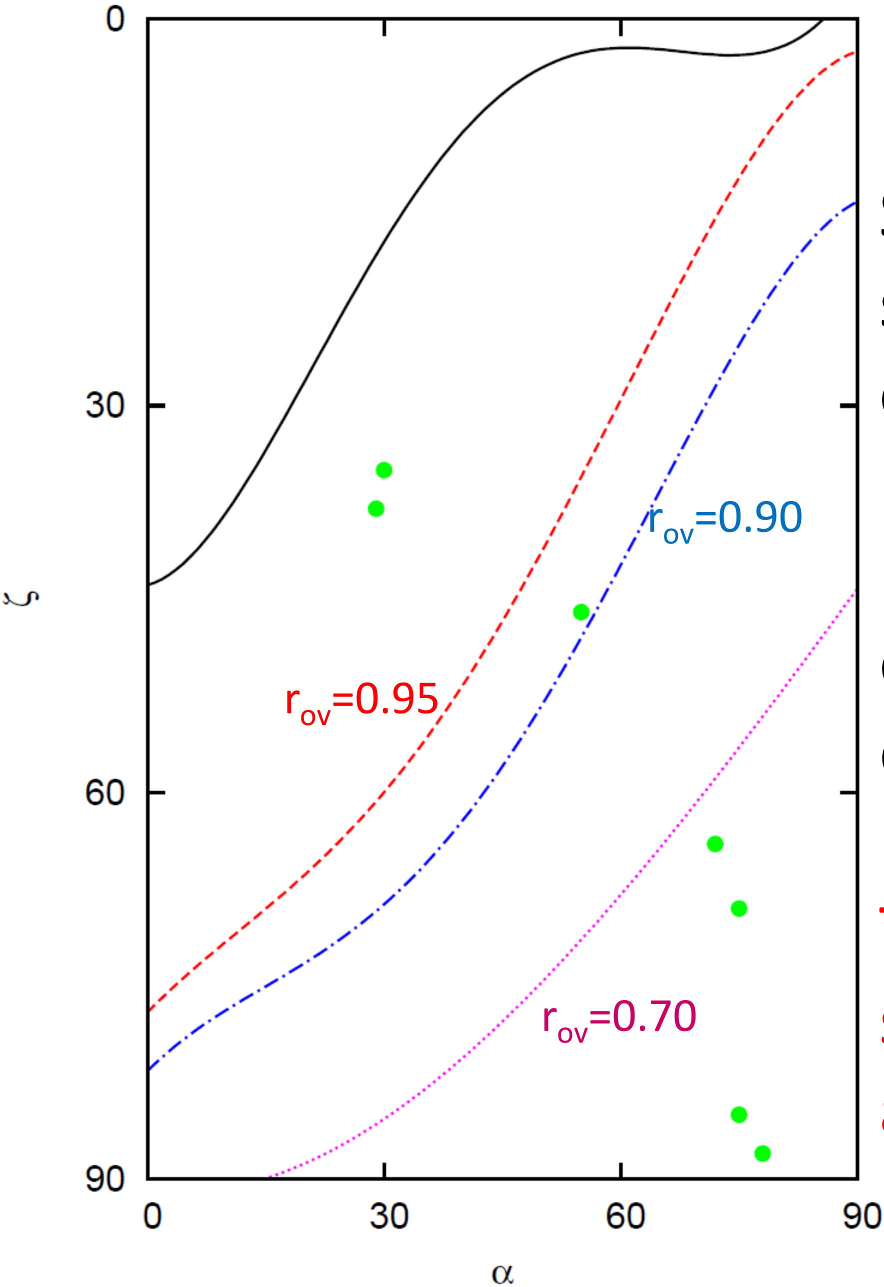


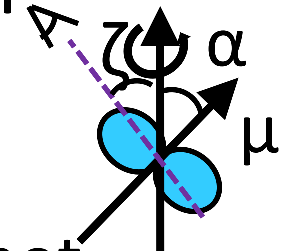
$$(1 - r_{ov}) \approx (L_{SD}/10^{33} ergs^{-1})^{-1/2}$$

(e.g. Watters et al. 2009)

The relations of r_{ov} with the other parameters are very weak.

Implication to the population study for γ-ray pulsars



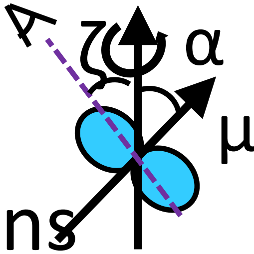


Since our model fits do not support that the lower boundary of emission region is assumed to be r_{ov} = 1.

If we adopt our r_{ov}-α relation, observable pulsars are incerased, especially pulsars with low-α and low-ζ.

This suggests a modification of statistics by previous works about observed γ-ray pulsars.

Summary



- We have calculated the light curves of emissions using the outer gap model and compared them with observed multi-wavelength light curves.
- We find that the model can successfully explain the peak positions of multi-wavelength light curves.
- We also find that the altitude of the emission region is correlated with inclination angle. This relationship is also very similar to that in a force-free magnetosphere.
- Number of the sources with low α and ζ increases compared with previous estimate.