The annular gap model:
radio and Gamma-ray emission of pulsars

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The annular gap model of pulsars

I. ***The Annular gap***

- **What is the Annular gap?**
- **What is the advantage of it ?**

II. Radio emission

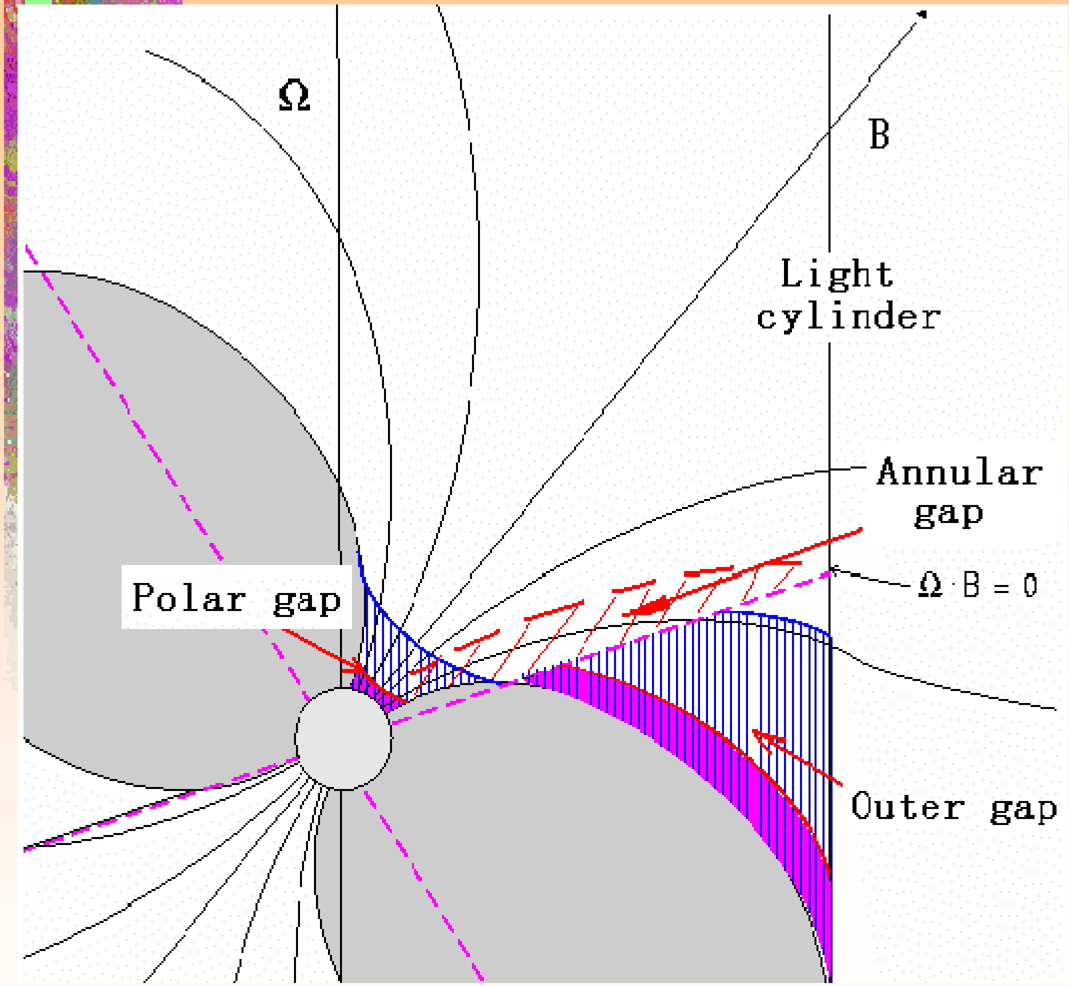
- inverse Compton scattering model
- Bi-drifting and annular gap

III. Gamma-ray emission

- The advantages of Polar gap and Outer gap model
- Annular gap model

IV. Some observational tests

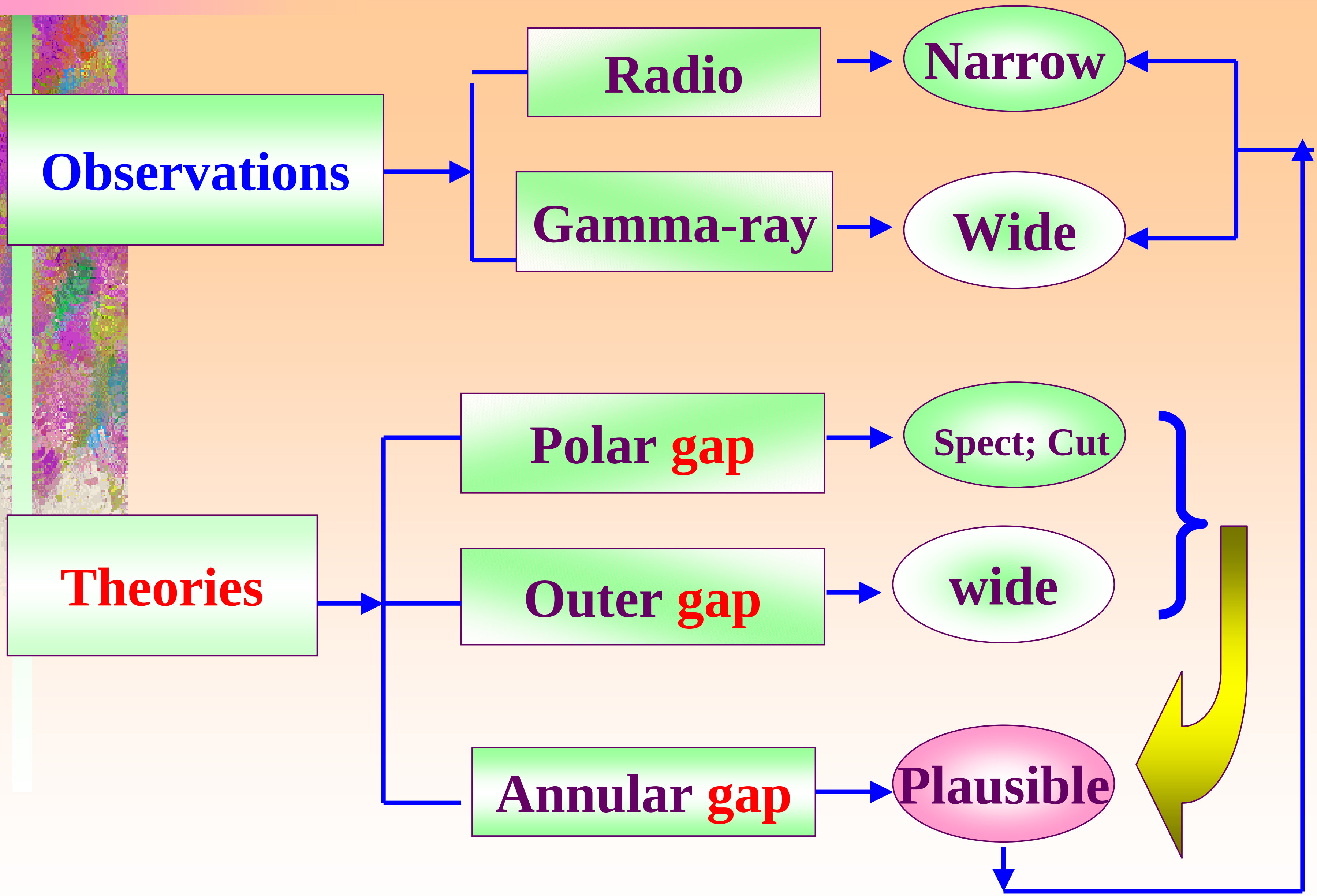
Where is the AG?
What is advantages of AG?



The advantages:

- Even if it's very near the surface, it still can get very wide emission beam
- It can fit both radio and gamma-rays at the same time!

A comparison between the models


Observations
Radio
Gamma-ray
Narrow
Wide
Theories
Polar gap
Outer gap
Annular gap
Spect; Cut
wide
Plausible

Pulsars are discovered 40 years

Key problems：

The nature of PSR: NS & Quark stars ?

Radiation: radiation mechanisms?

Polar gaps? Outer gaps?

or ··· *Annular gaps*?

Basic observational facts

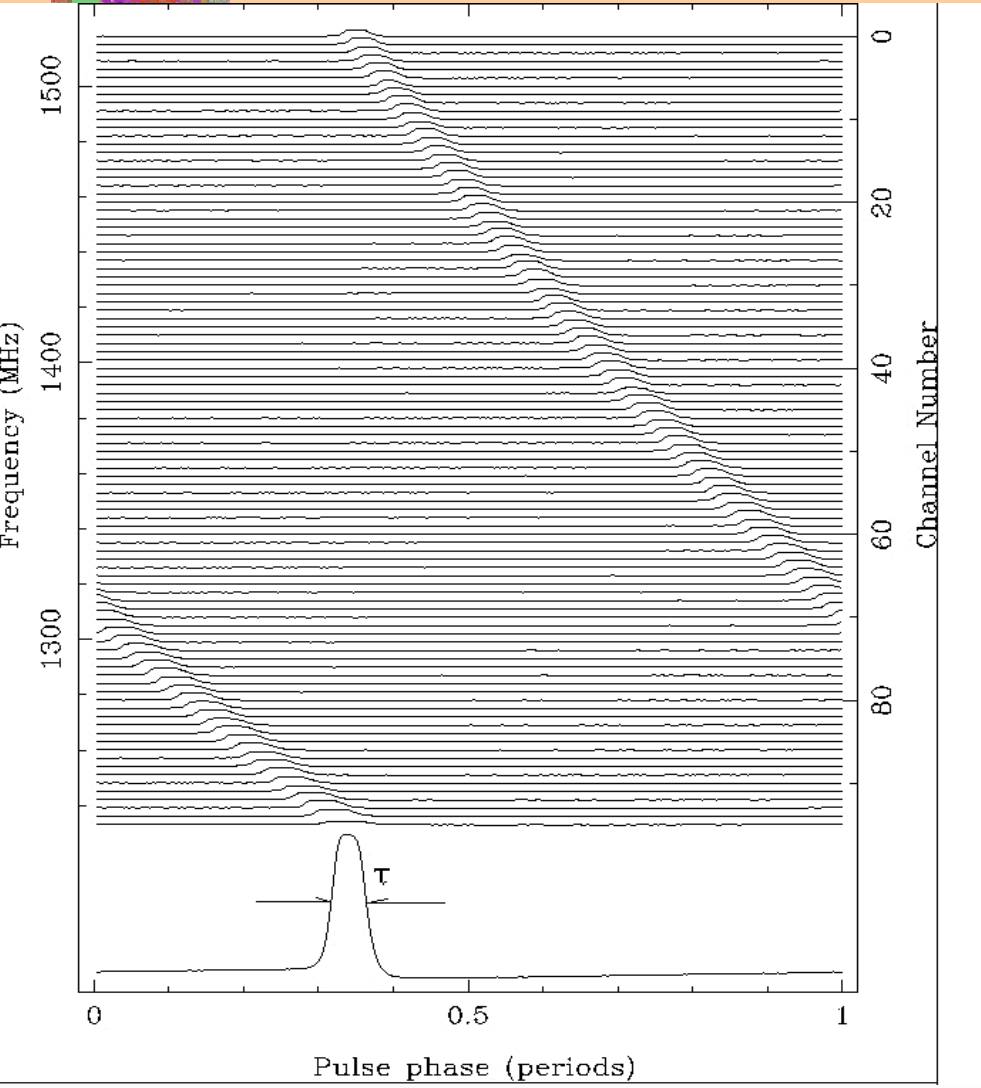
1.Radio

- ★ **pulse profiles:**
  narrow; changing with frequencies
- ★ *polarization: linear, circular*
- ★ *Mode changing*
- ★ *Drifting sub-pulse*
- ★ *Core emission & conal emission*

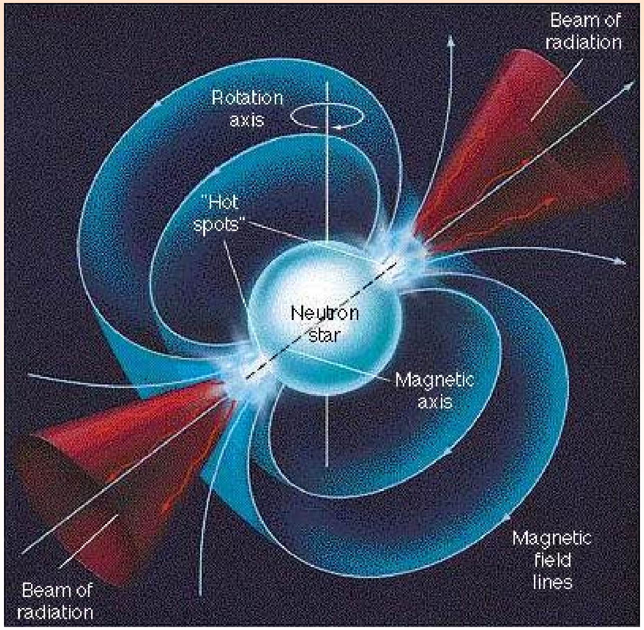
2.Gama-ray emission

- ★ **wide emission beams**
- ★ **harder emission at the bridge**
- ★ **high energy cut-off**

Radiation beam: **narrow**

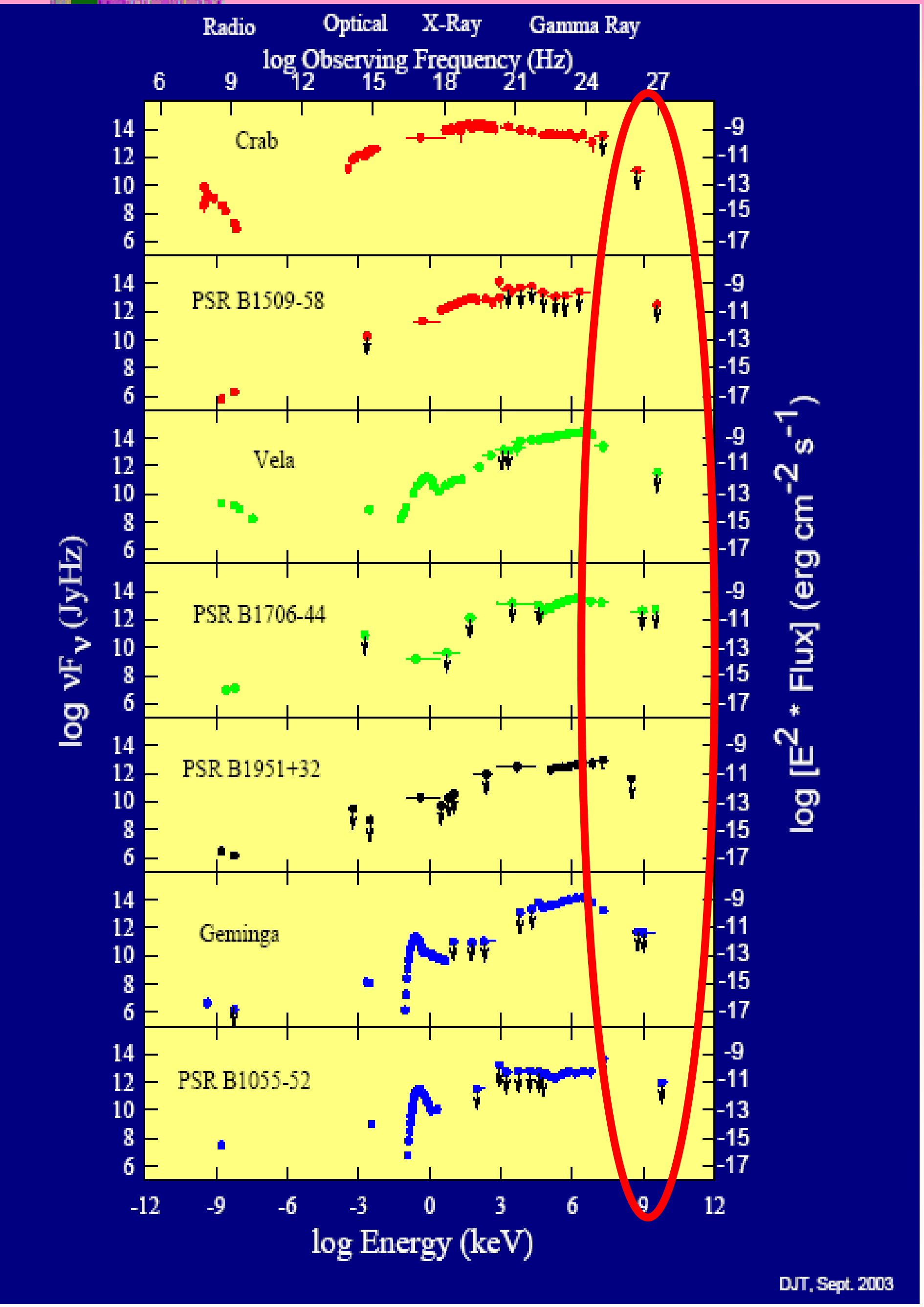


τ /P ≈ 3% - 4%
the window ≈10-20 degrees it does not related with
P & B
→ **Close to the surface**



Manchester,R.N., 3003

- **Wide** emission beams
- High energy **cut off**
- **Harder** bridge emission



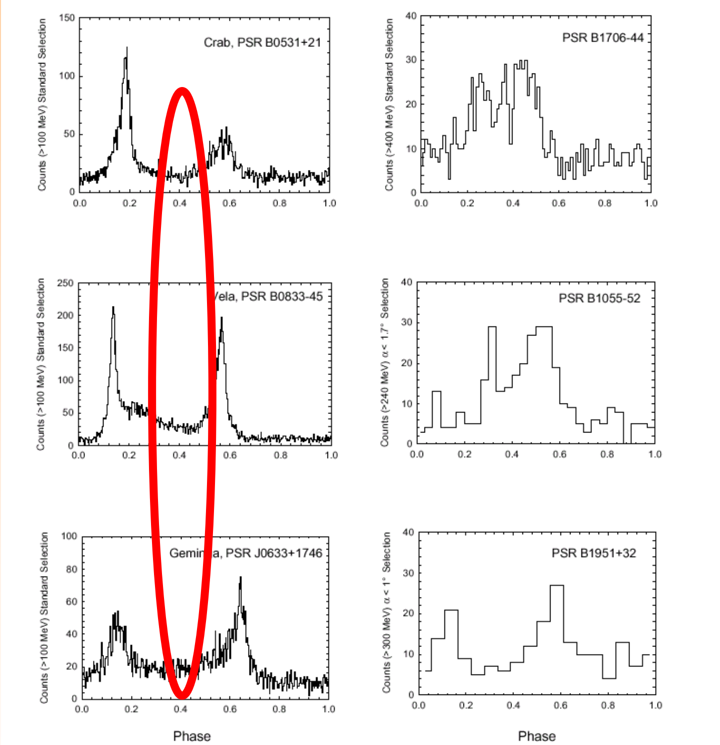


Fig. 2. High-energy light curves of γ-ray pulsars (> 100 MeV, unless indicated differently)

Thompson, astro-ph/0312272 , Kanbach, 2002,astro-ph/0209021

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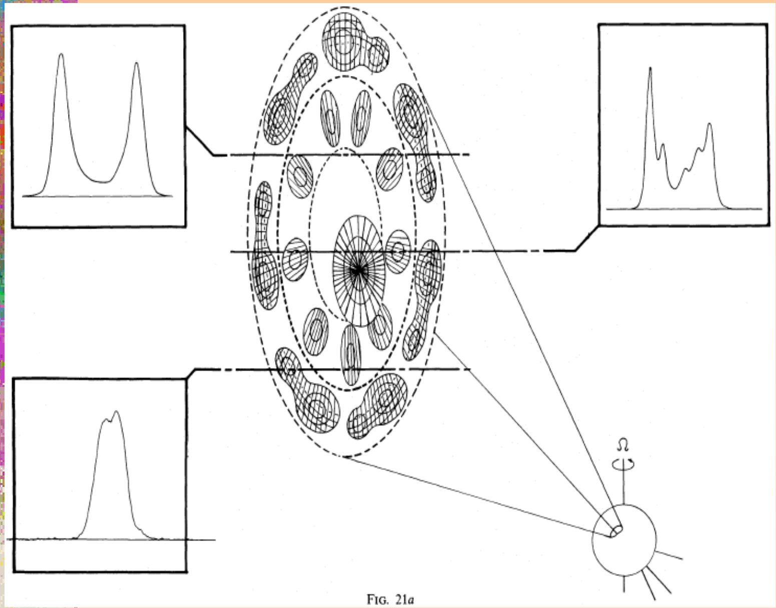
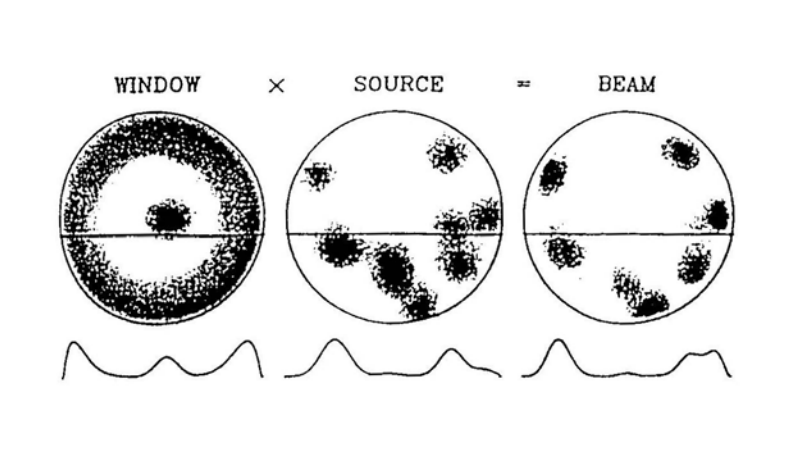
Core and conal emission beams



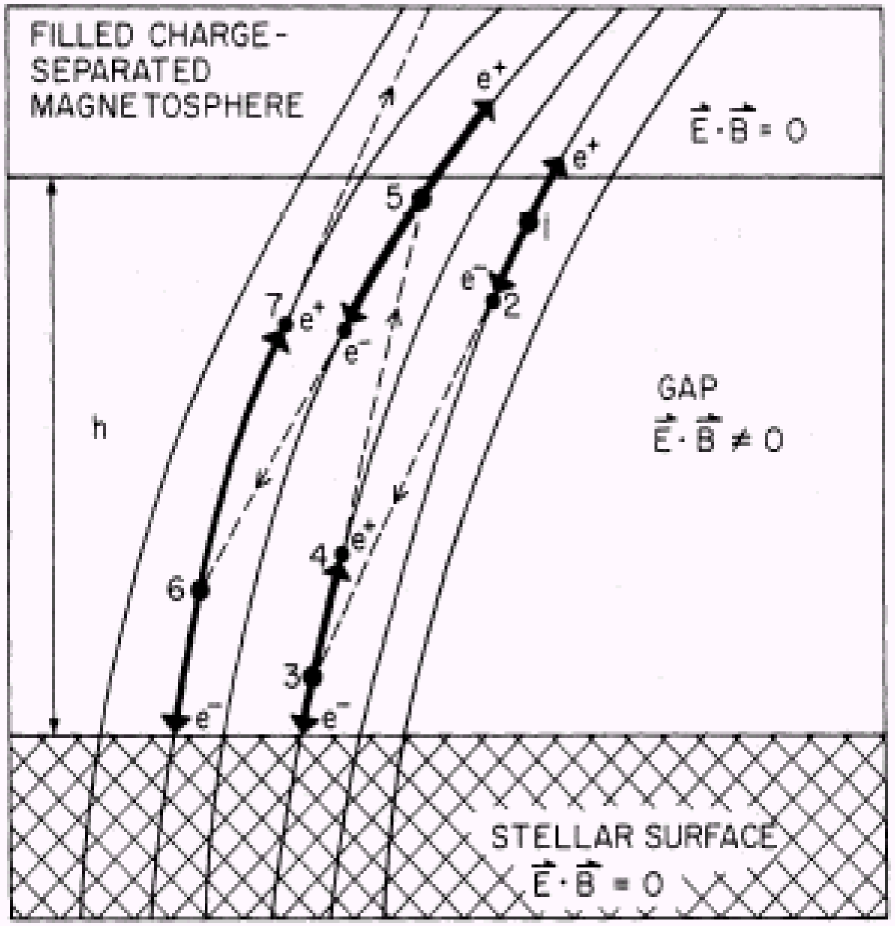


Rankin, 1983, ApJ,274,333

Manchester,R.N. 1995
J. Astroph. Astr. 16,107

→ ***Core emission !***

Inner polar vacuum gap



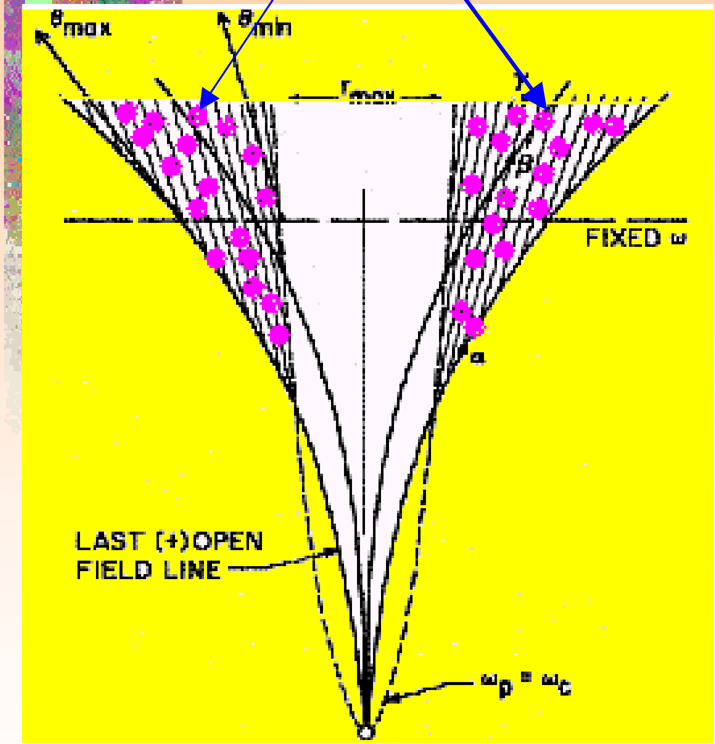
GAP

$\vec{E}\cdot\vec{B} \neq 0$

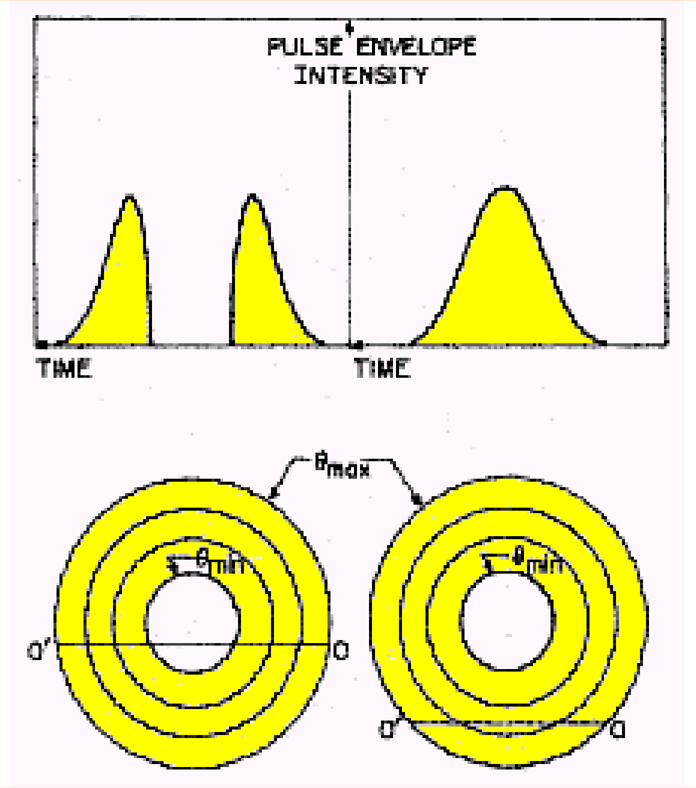
Ruderman & Stherland 1975

Emission beams in RS model

Emission beams

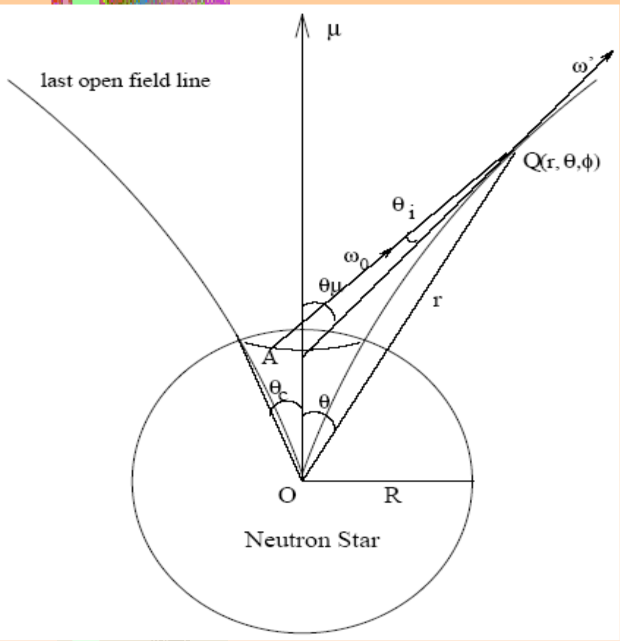


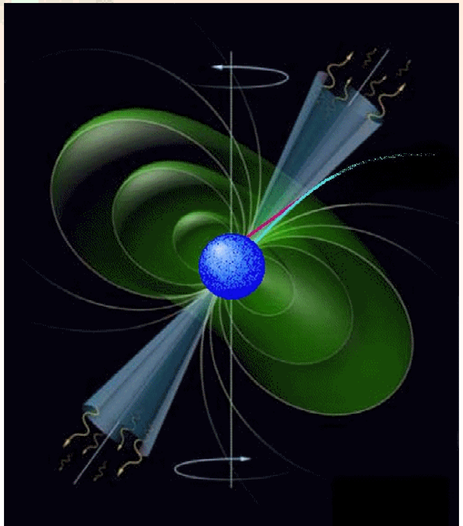
Ruderman & Sutherland, 1975

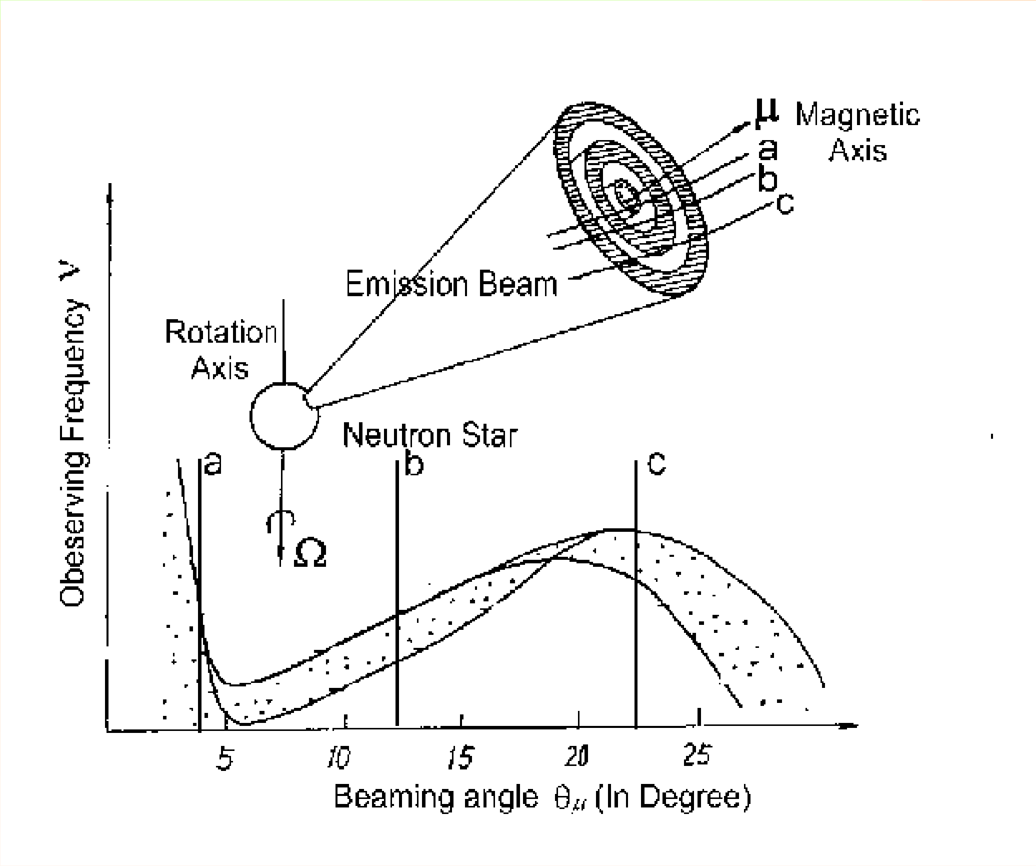


Hollow cone only!
Low freq: wide beam!

Inverse Compton scattering (ICS) model

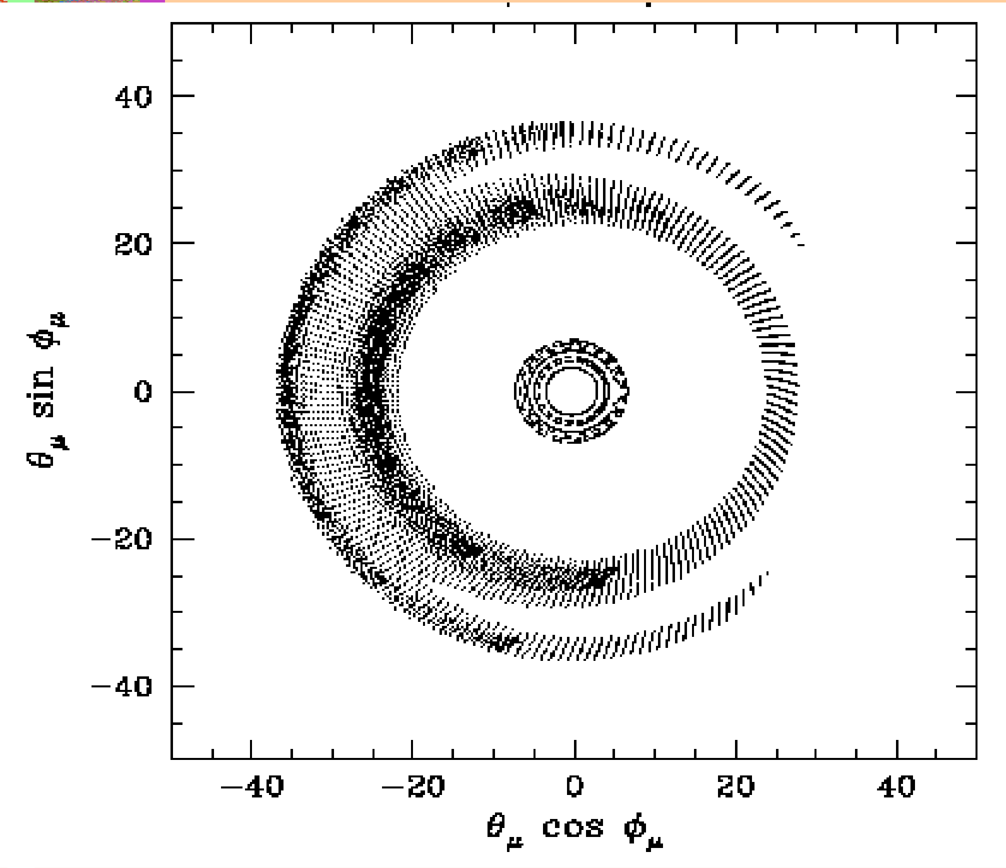


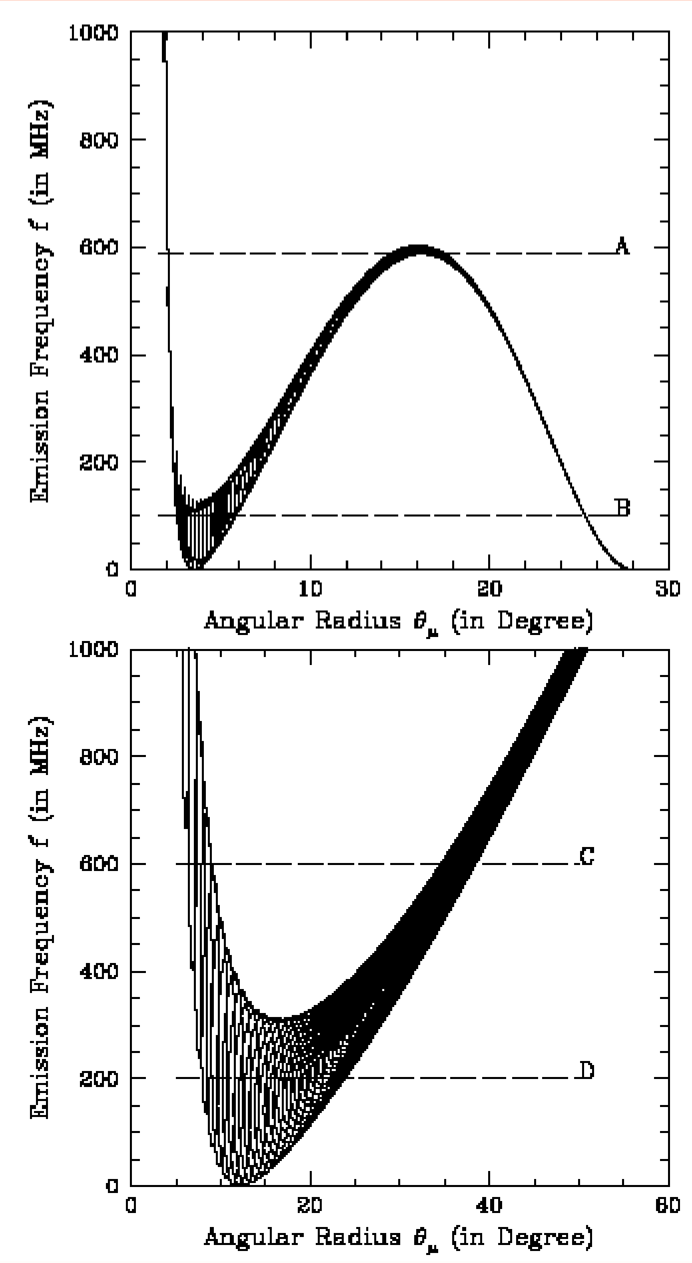




Qiao, 1992

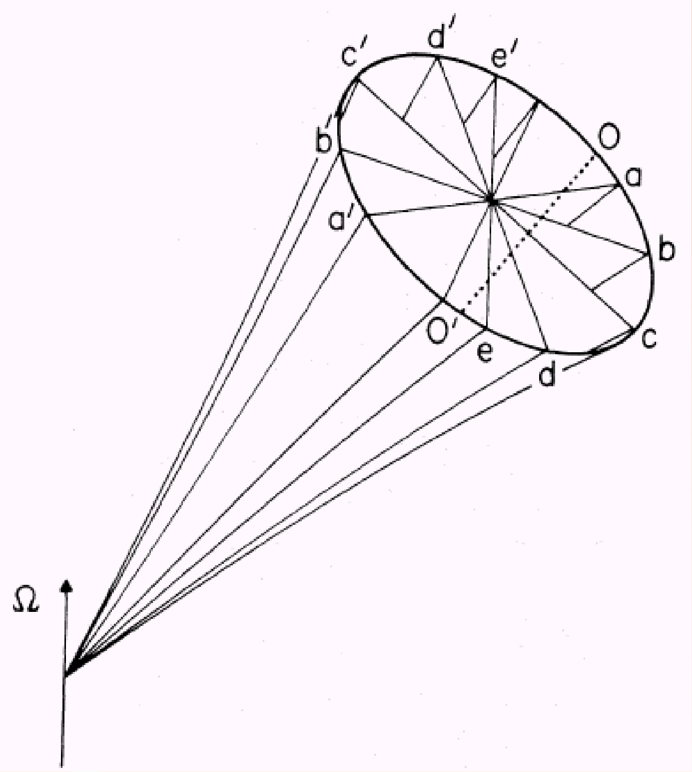
ICS: Beaming frequency figure

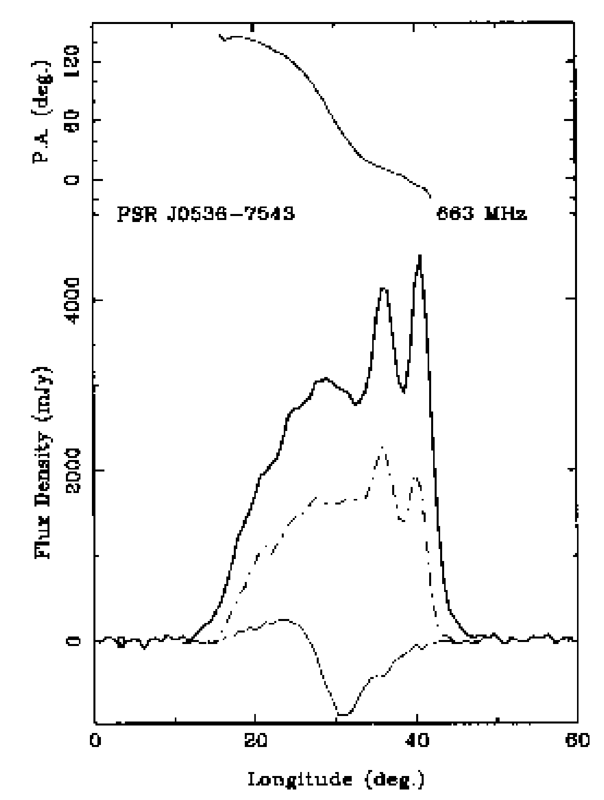


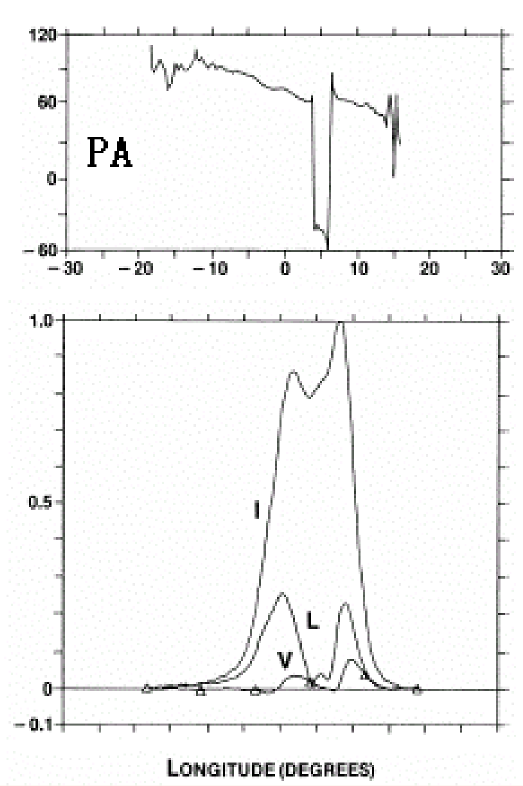


Qiao & Lin, 1998, AA;
Qiao,Lin, Zhang,& Han, 2001,AA

Position angle (PA): "S" shape



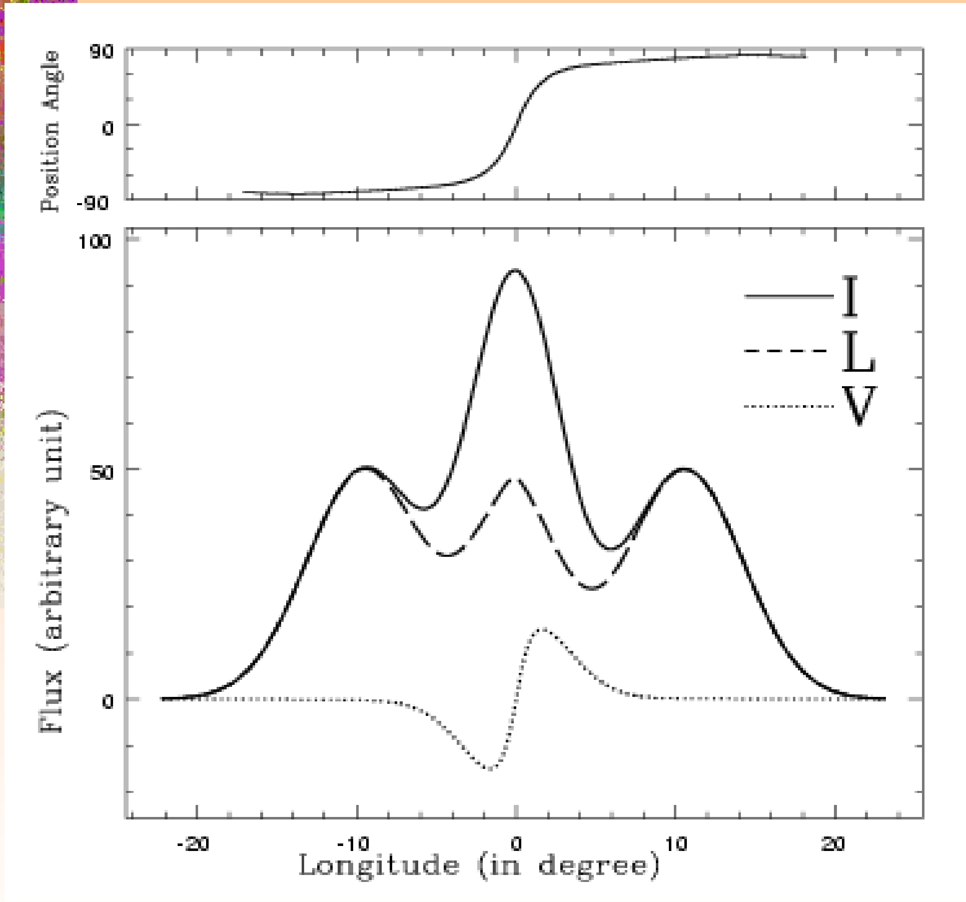




→ Radiation location: polar cap region

Polarization of integrated pulse in ICS

(Xu et al. ApJ.2000)



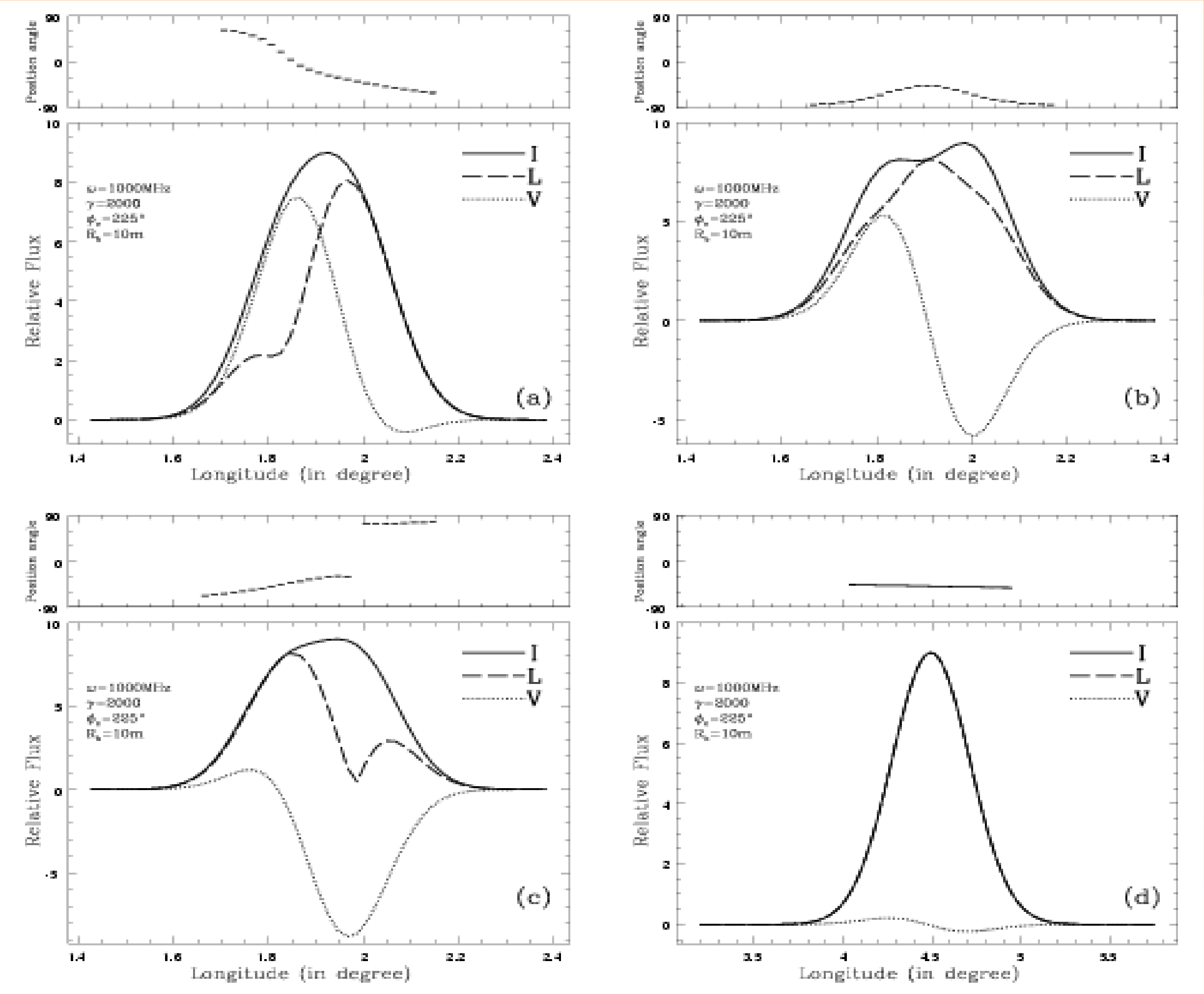
Position angle:PA

I—Total Intensity

L—Linear poln

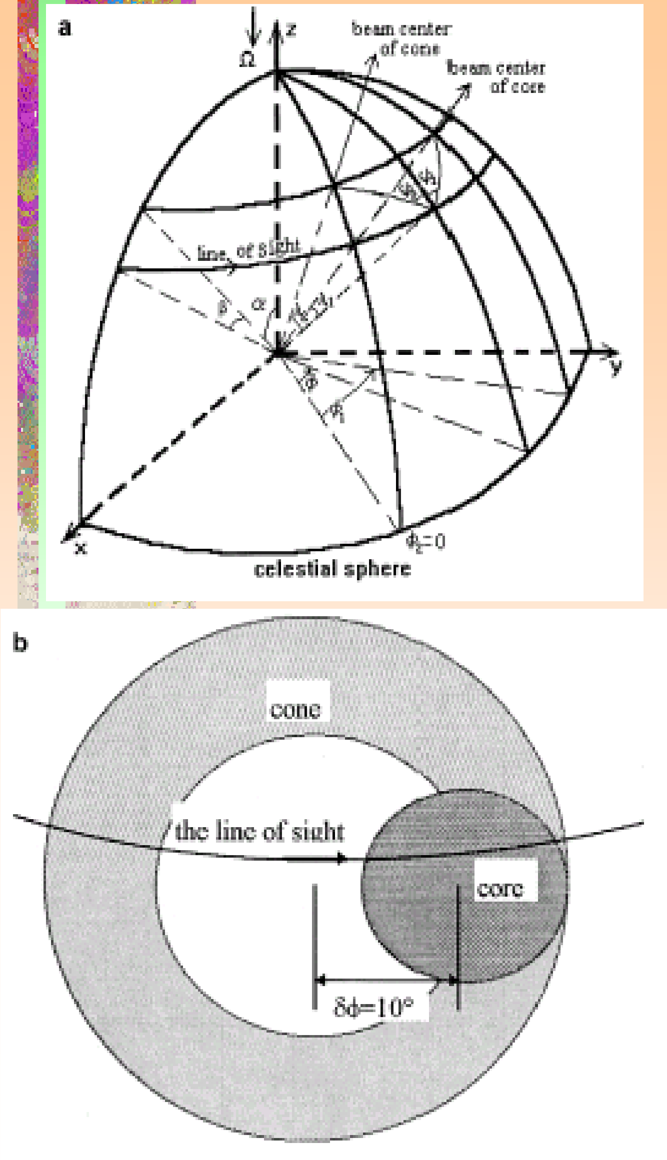
V—circular poln

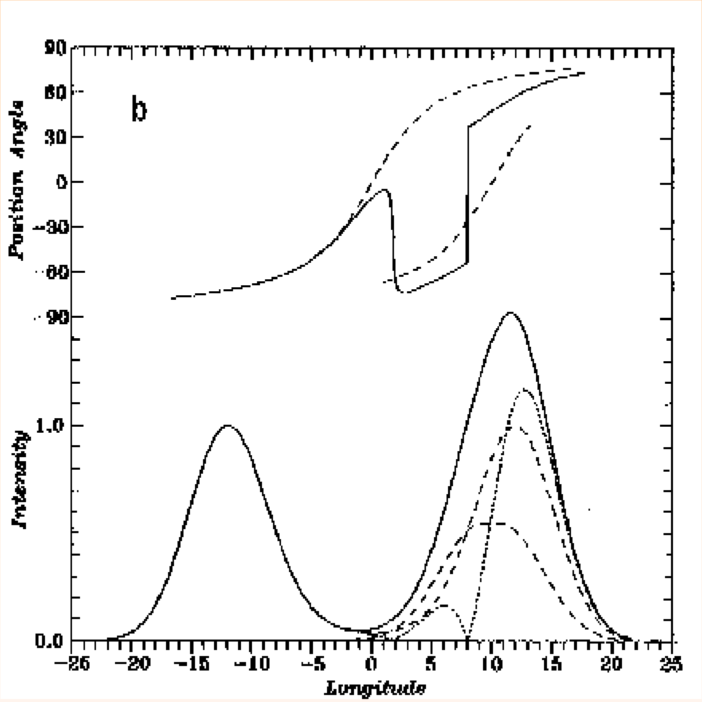
Polarization of Individual pulses in ICS model



Xu et al. ApJ. 2000

Polarization: Beam shift→PA jumps





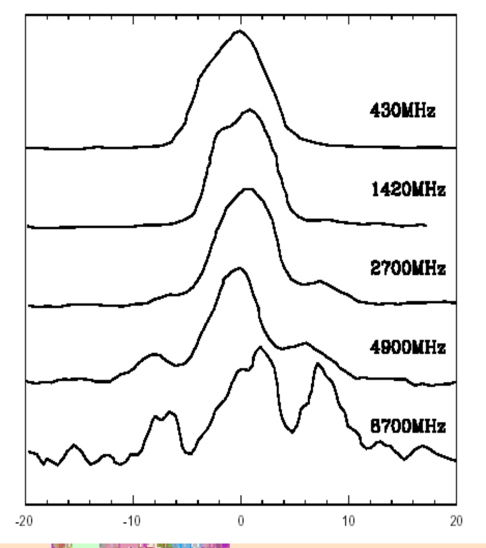
Xu, Qiao & Han, 1997, AA

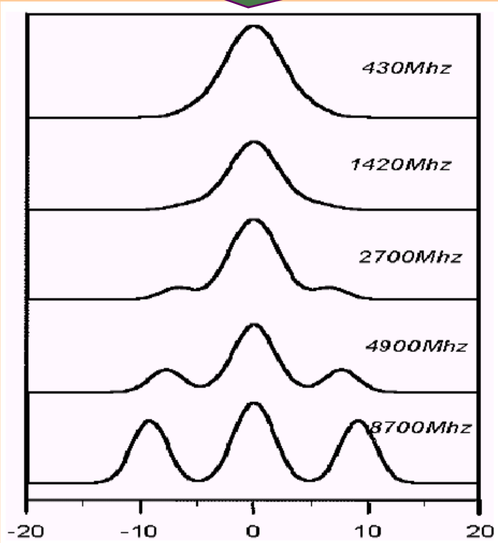
Obs.

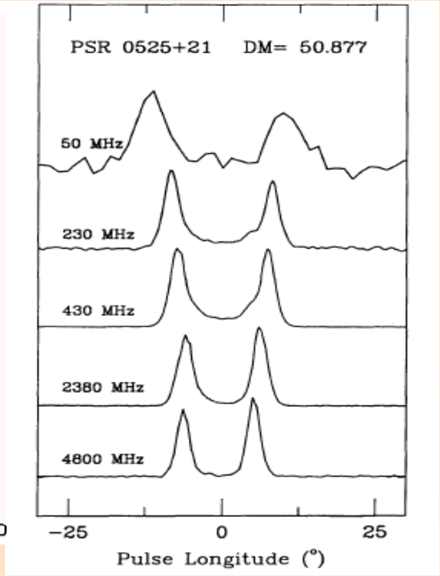
ICS model

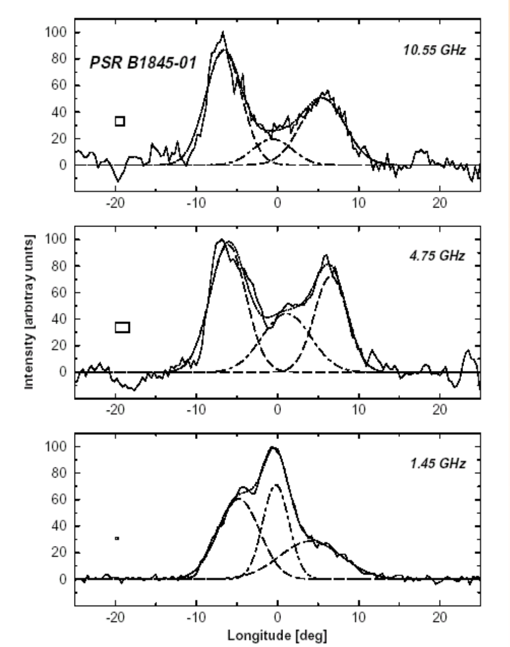
?

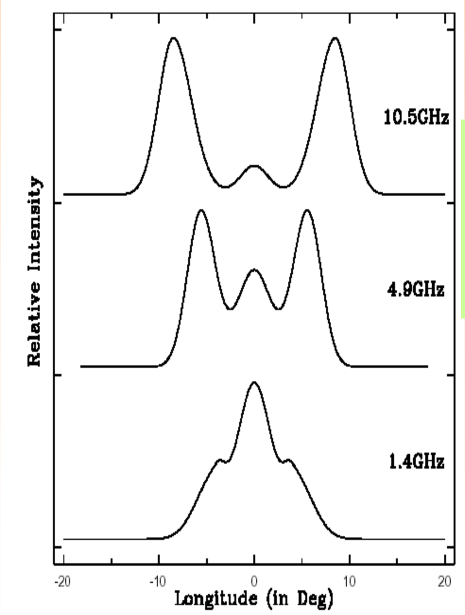
RS model











The beaming frequency variation!

Qiao,Liu, Zhang,& Han, 2001,AA

Lyne & Manchester (1988) & Sieber et al. (1975),Kramer,(1994)

Different gap heights:mode changing

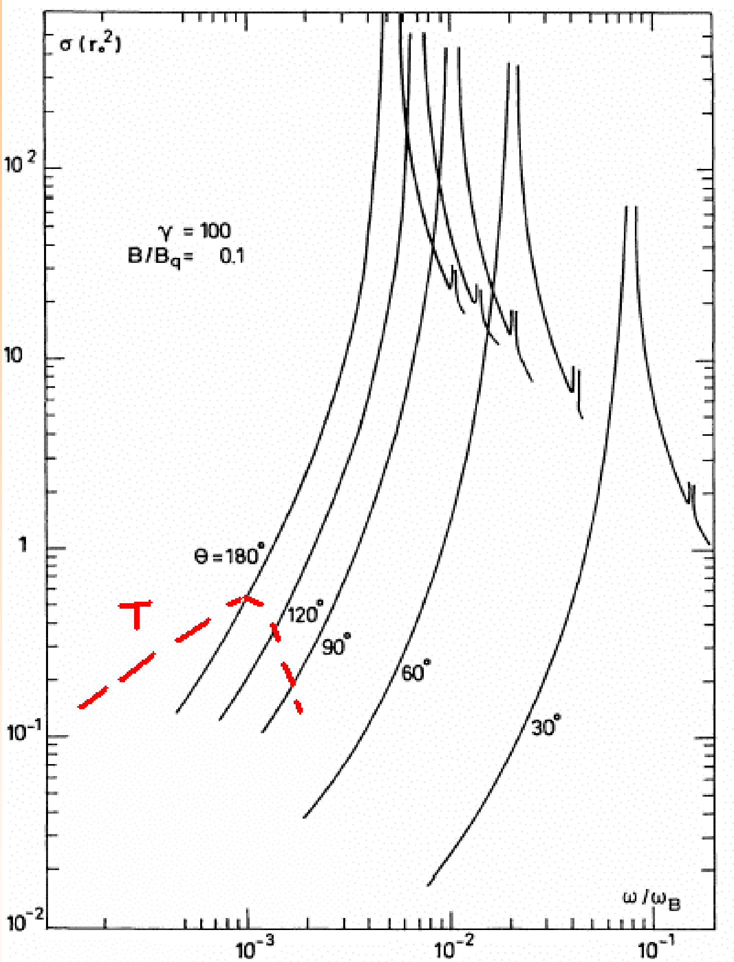
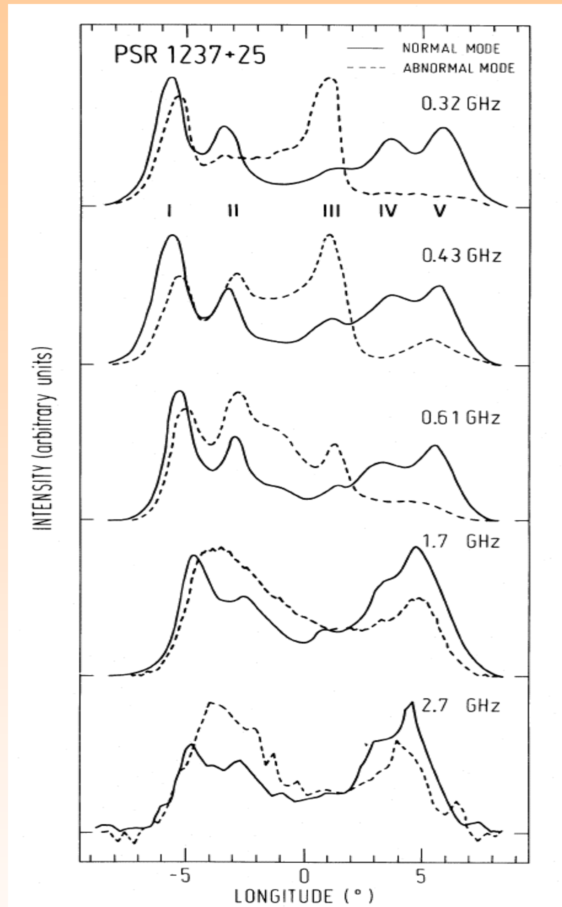
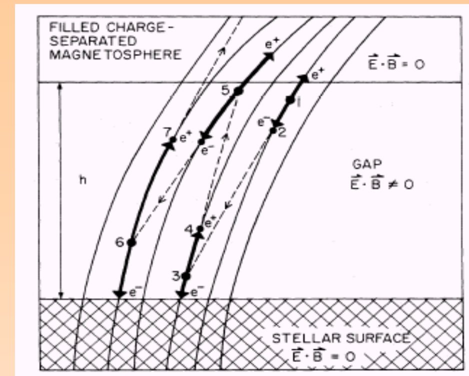


Fig. 1. Total cross sections (unpolarized) in units of r_0^2 vs. frequency ω in units of ω_B, for different photon incoming angles $\theta = 30°, 60°, 90°, 120°, 150°, 180°$





Rankin, 1986

the γ-B pair production process

$$l = \frac{4.4}{e^2/\hbar c}\,\frac{\hbar}{m_e c}\,\frac{B_q}{B_\perp}\exp\left(\frac{4}{3\chi}\right), \quad \chi \ll 1\,,$$

$$\chi \equiv \frac{E_\gamma}{2m_e c^2}\,\frac{B_\perp}{B_q} \equiv \frac{E_{\gamma\perp}}{2m_e c^2}\,\frac{B}{B_q}$$

$$E_{\gamma,\mathrm{CR}} = \hbar\omega_{c,\mathrm{CR}} = \hbar\,\frac{3}{2}\,\frac{\gamma^3 c}{\rho}\,,$$

$$E_{\gamma,\mathrm{res}} \sim 2\gamma^2\hbar\omega_{\mathrm{res}}(1-\beta\mu_i) = 2\hbar\gamma\omega_B\,,$$

$$\omega_B = eB/mc$$

$$E_{\gamma,\mathrm{th}} \sim 2\gamma^2\hbar\omega_m(1-\beta\mu_i)\,,$$

Zhang,Qiao,Lin,Han,1997,ApJ.

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- Why other authors do not suggest it for a long time?

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The annular gap model of pulsars

- The advantages of Polar gap

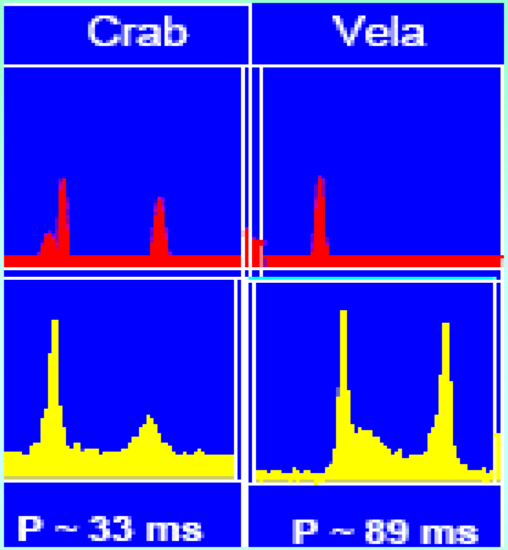
  1. To fit **Crab** like PSR;
  2. High energy **cut off**;
  3. **Hardness** of Bridge;

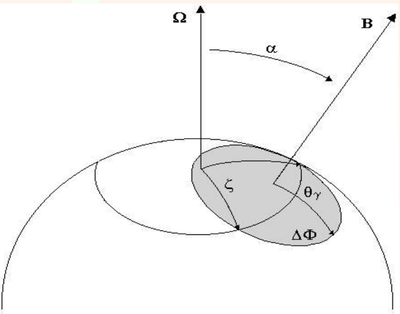
- The advantages of Outer gap model

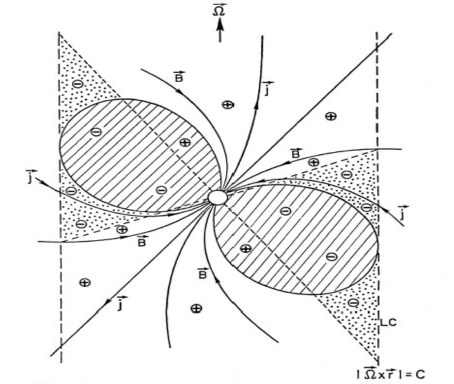
  1. It can fit **Vela** like PSR;
  2. **Wide** emission beams of Gamma-rays;

- Annular gap model

  Can have both of them!

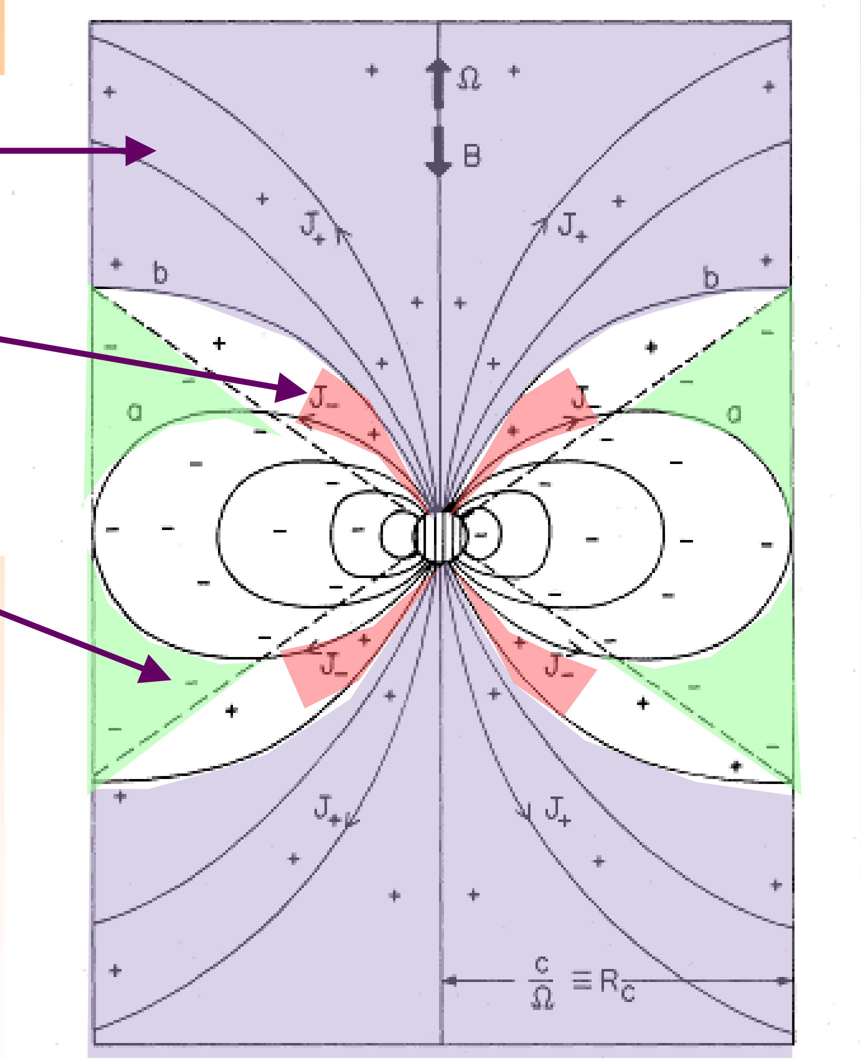






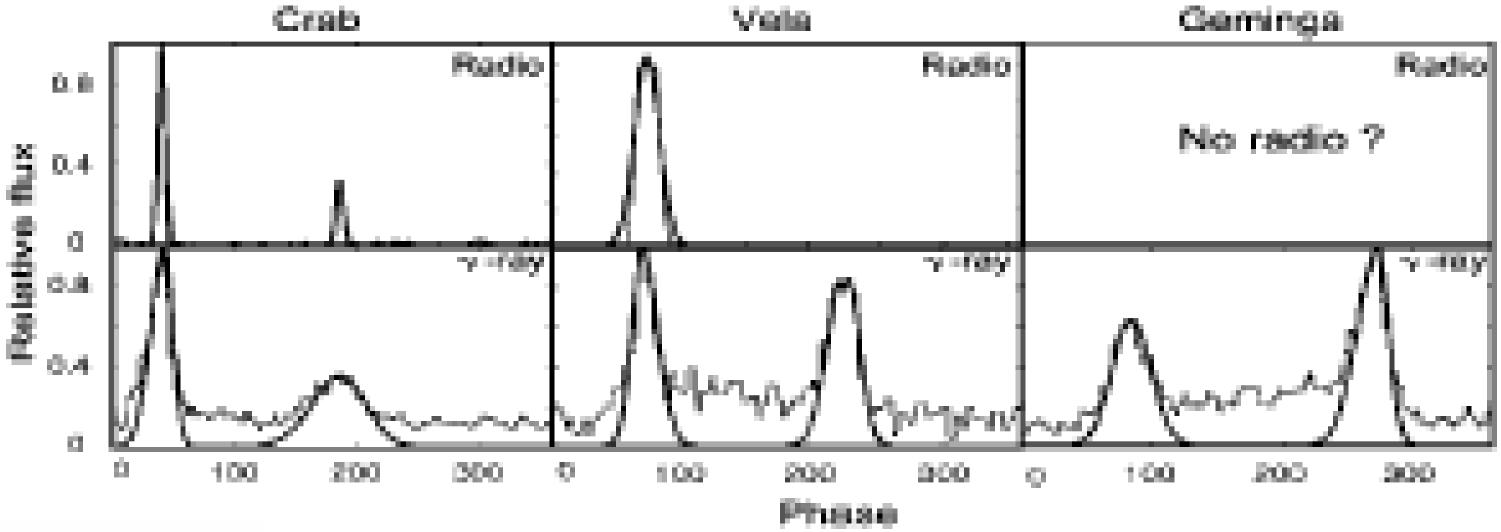
Two polar cap regions

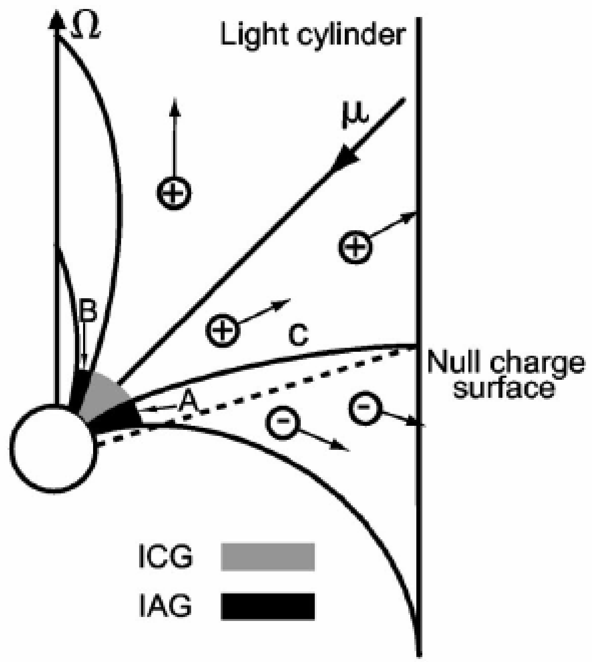
- Core region
- Annular region
- Outer gap



Qiao et al.
2004,ApJ.,a,b
astro-ph/0704.3801

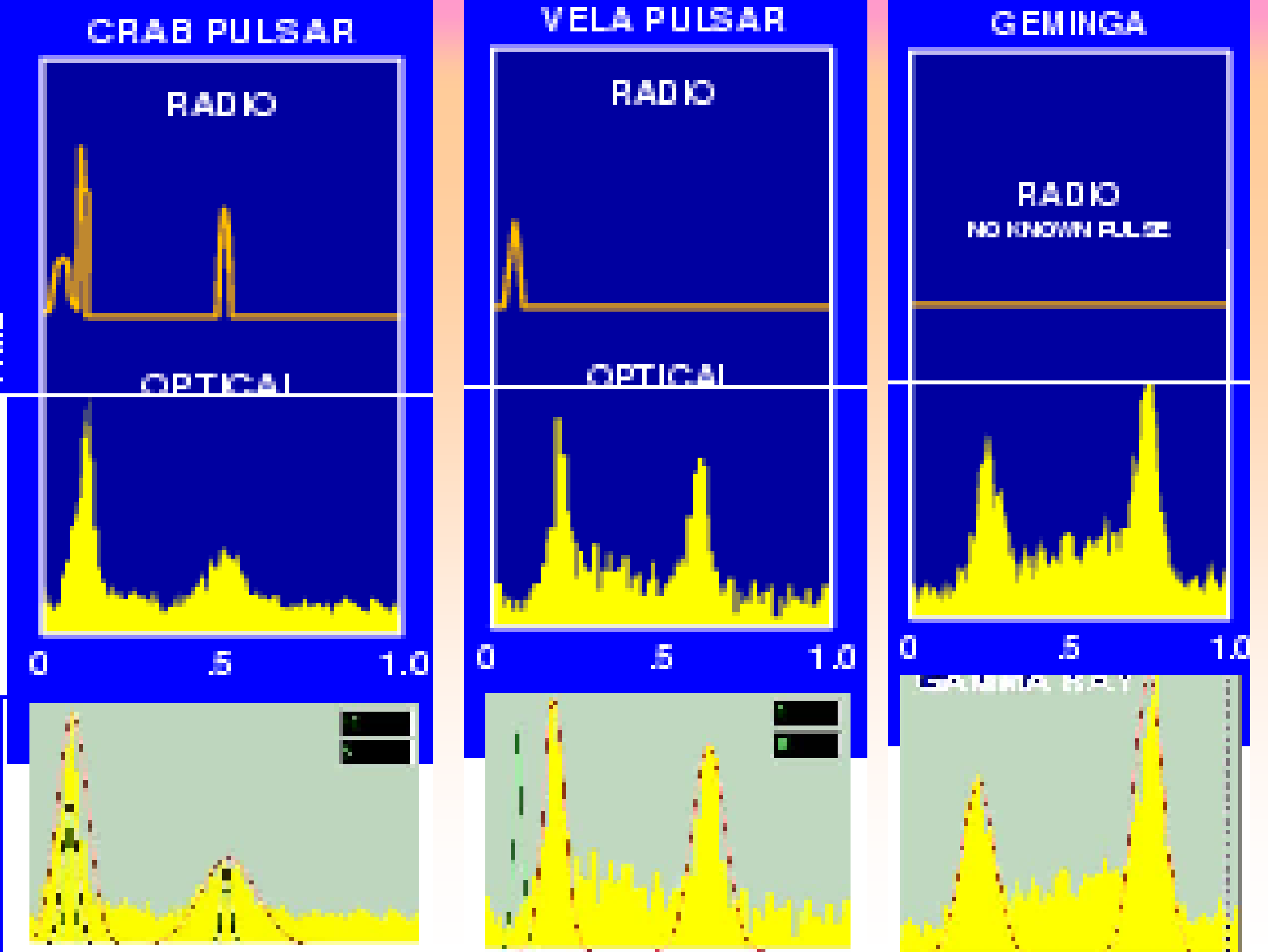
The Inner Annular Gap

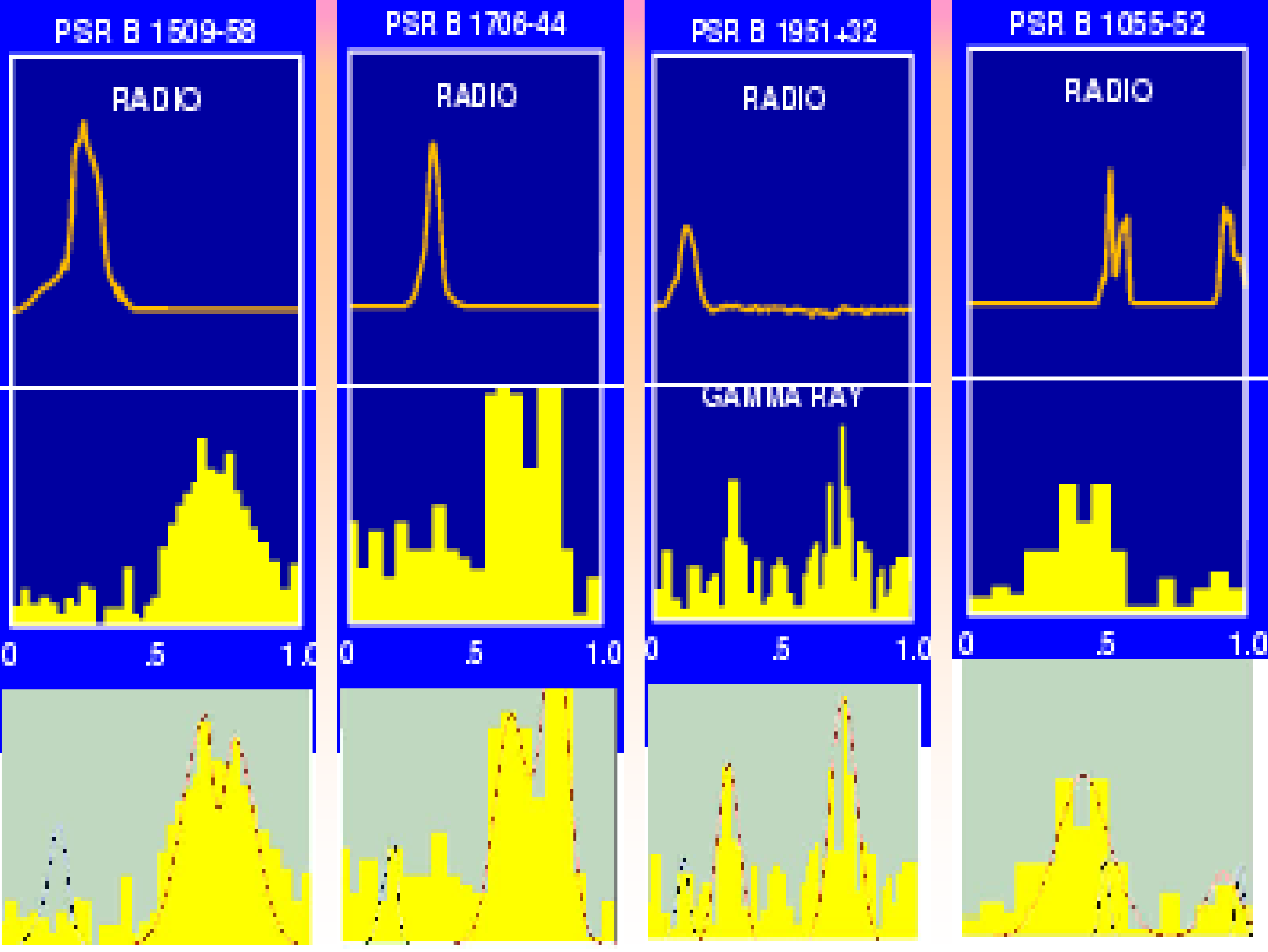




The radio and gamma-ray can be understood by annular gap at same time.

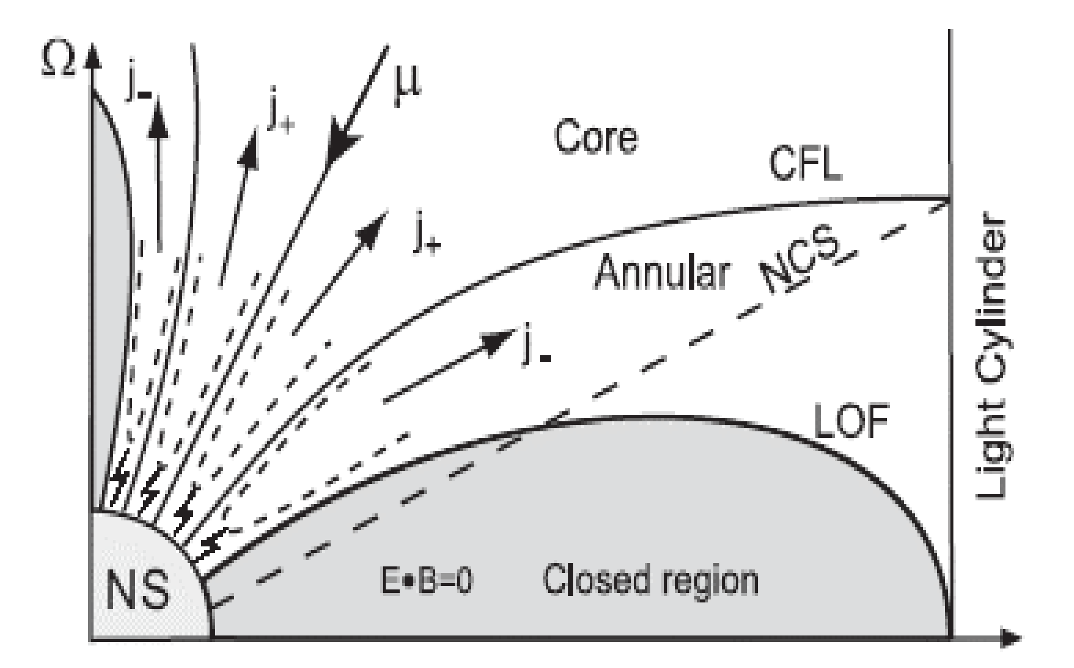
Qiao,Lee,Wang,Xu,Han 2004a, ApJL


CRAB PULSAR
RADIO
OPTICAL
0
.5
1.0
VELA PULSAR
RADIO
OPTICAL
0
.5
1.0
GEMINGA
RADIO
NO KNOWN PULSE
0
.5
1.0



PSR B 1509-58
RADIO
0
.5
1.0
PSR B 1706-44
RADIO
0
.5
1.0
PSR B 1951+32
RADIO
GAMMA RAY
0
.5
1.0
PSR B 1055-52
RADIO
0
.5
1.0

Free flow: slot gap & Annular gap



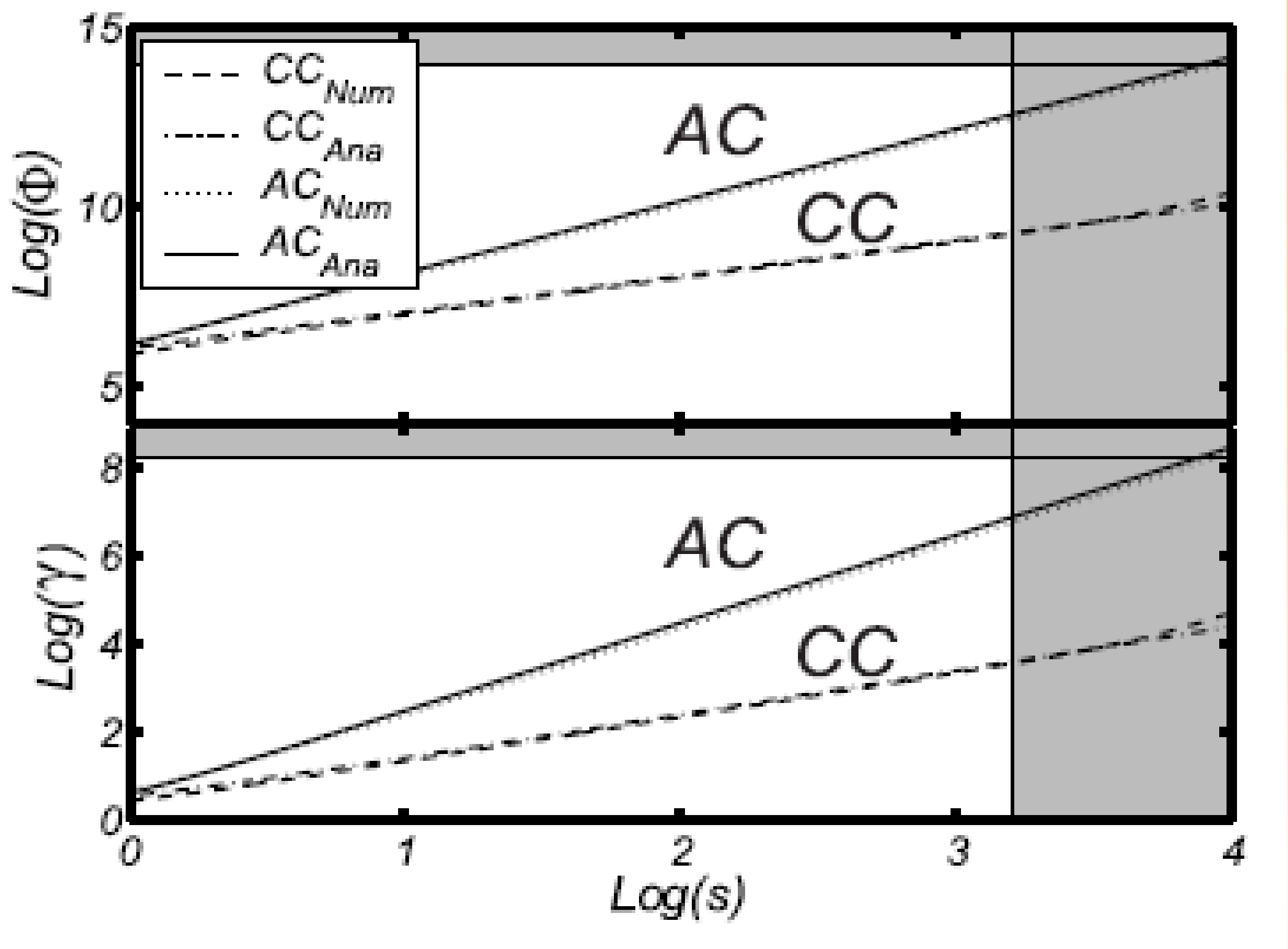
(1) $E_{\parallel} = 0$ at the surface level

(2) $\Phi = 0$ at the surface and at the interface between the closed magnetosphere and the open field lines

(3) It does not a Fully charge separated magnetosphere

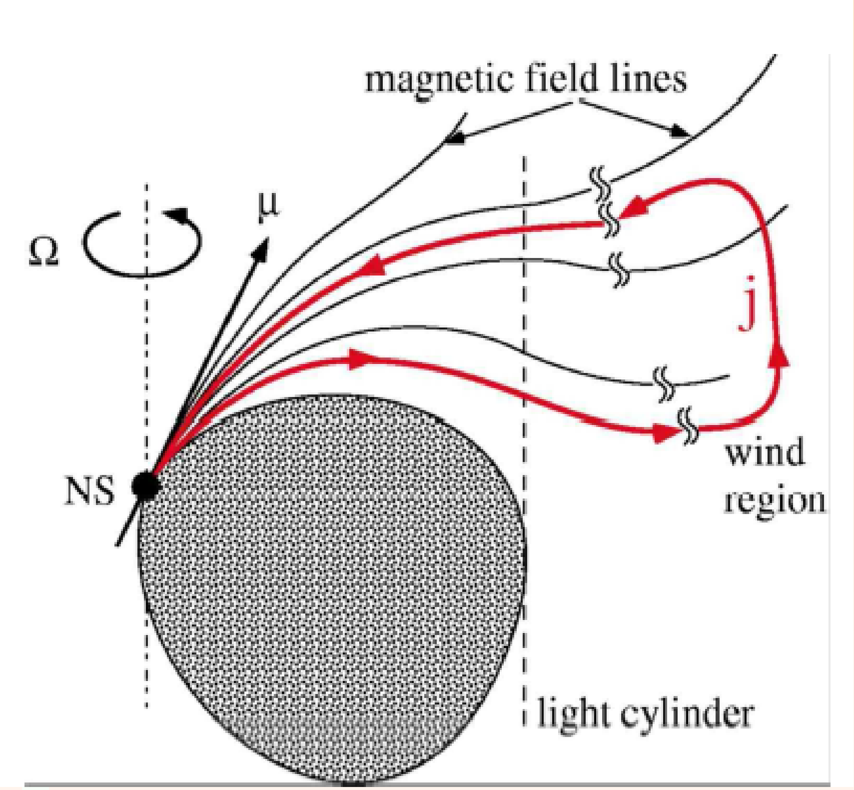
Qiao,Lee,Zhang,Wang, Xu, 2007,ChJAA,9, 496

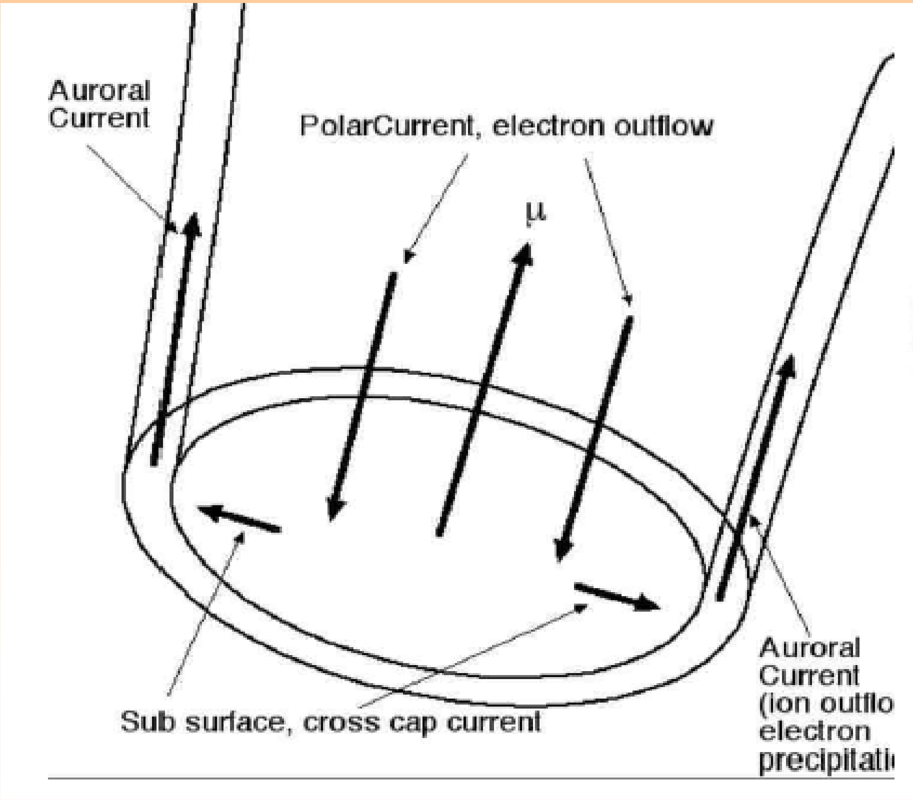
The annular gap



the acceleration effect of AG is much higher efficiency!

Primary polar current and the return current





How can we Get this?

Arons,2007

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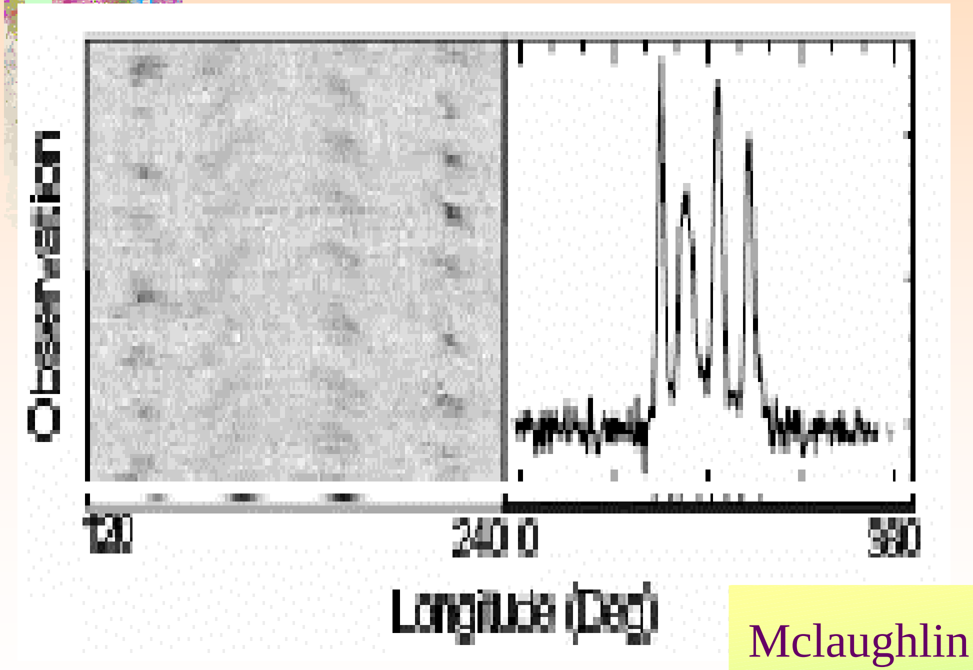
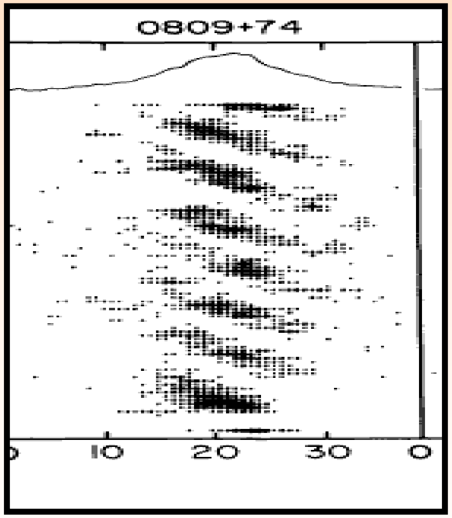
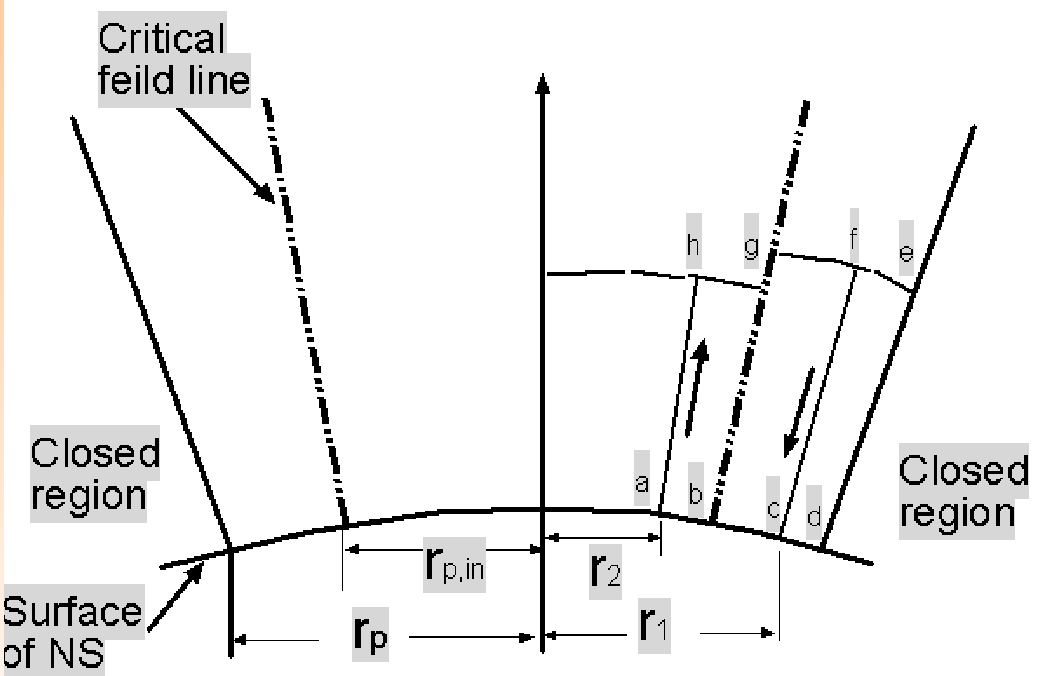
- Bi-drifting phenomena;
- The beaming frequency variation;
- Multi-beam observational constraints





Mclaughlin 2003,astr-ph/0310454

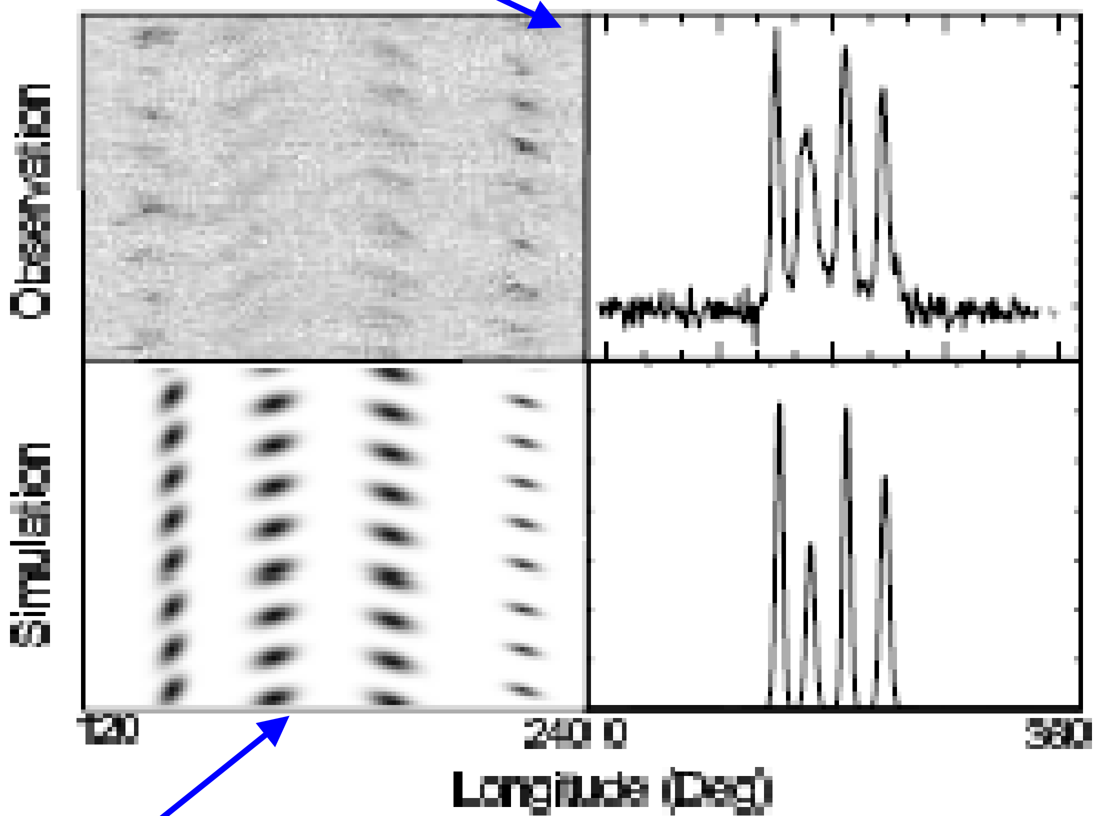
Inner Annular Gap : $\mathbf{V} = \dfrac{c\,\mathbf{E} \times \mathbf{B}}{B^2}$



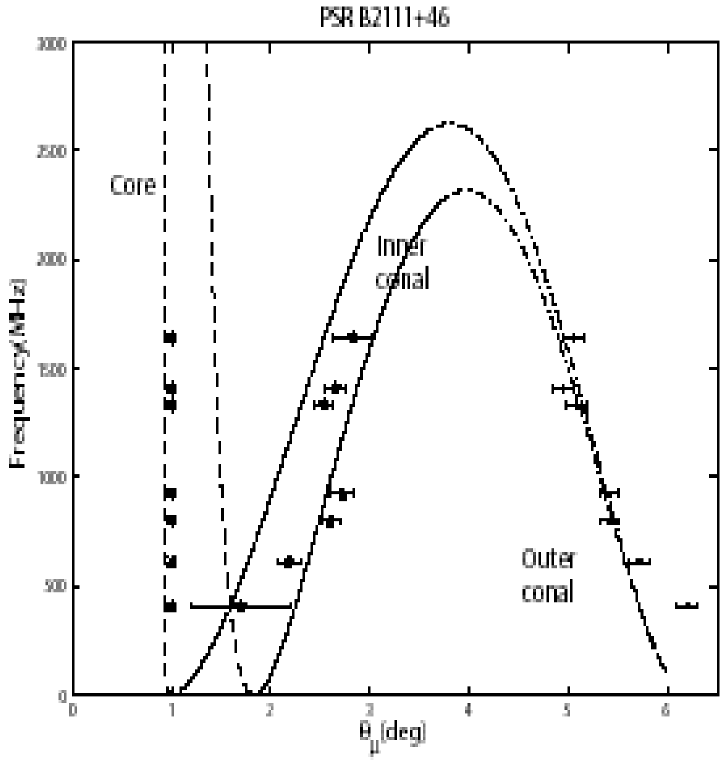
$$\mathbf{v} = \mathbf{E} \times \mathbf{B} / |\mathbf{B}|^2$$

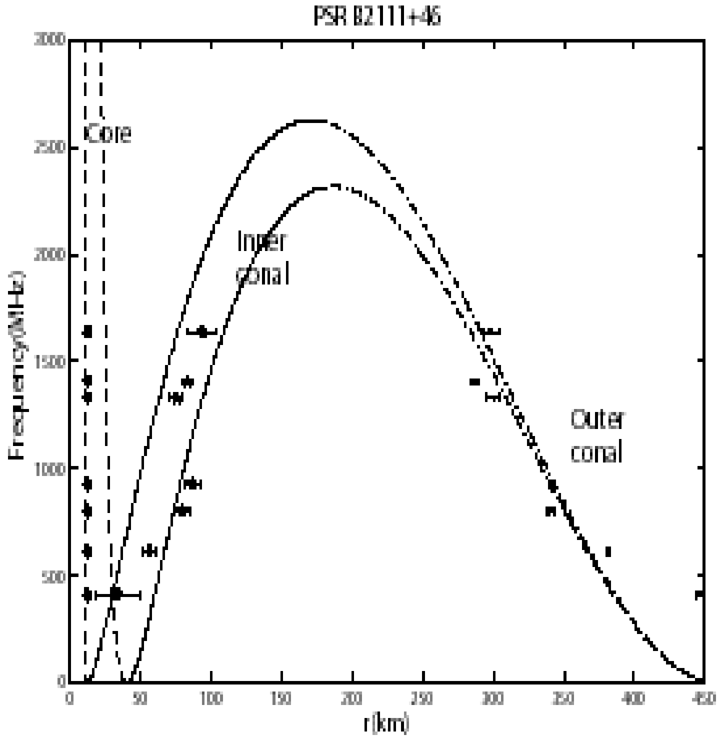
Bi-drifting: fitting

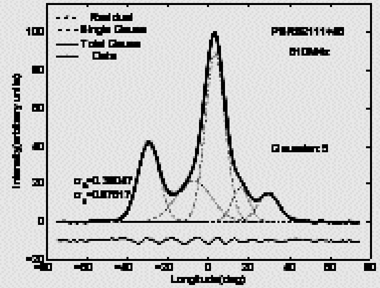
Mclaughlin 2003,astr-ph/0310454

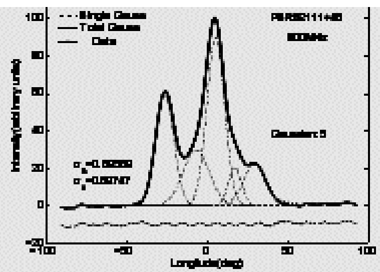


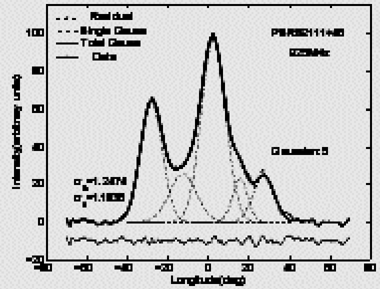
Qiao,Lee,Zhang,Xu,Wang,2004b, ApJL

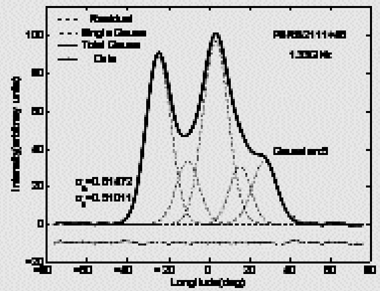


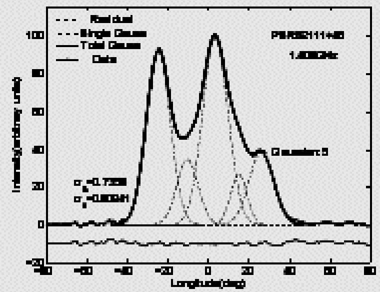












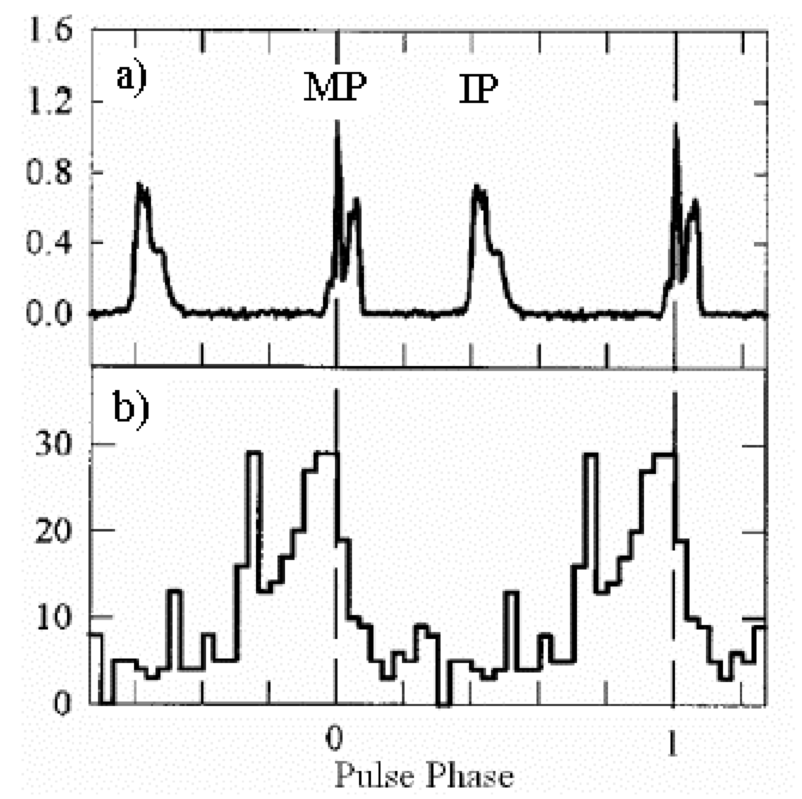
Different components of same frequency come from different altitudes.

Zhang, Qiao, Han, Lee, Wang , AA,2007

Multi-beam observational constraints

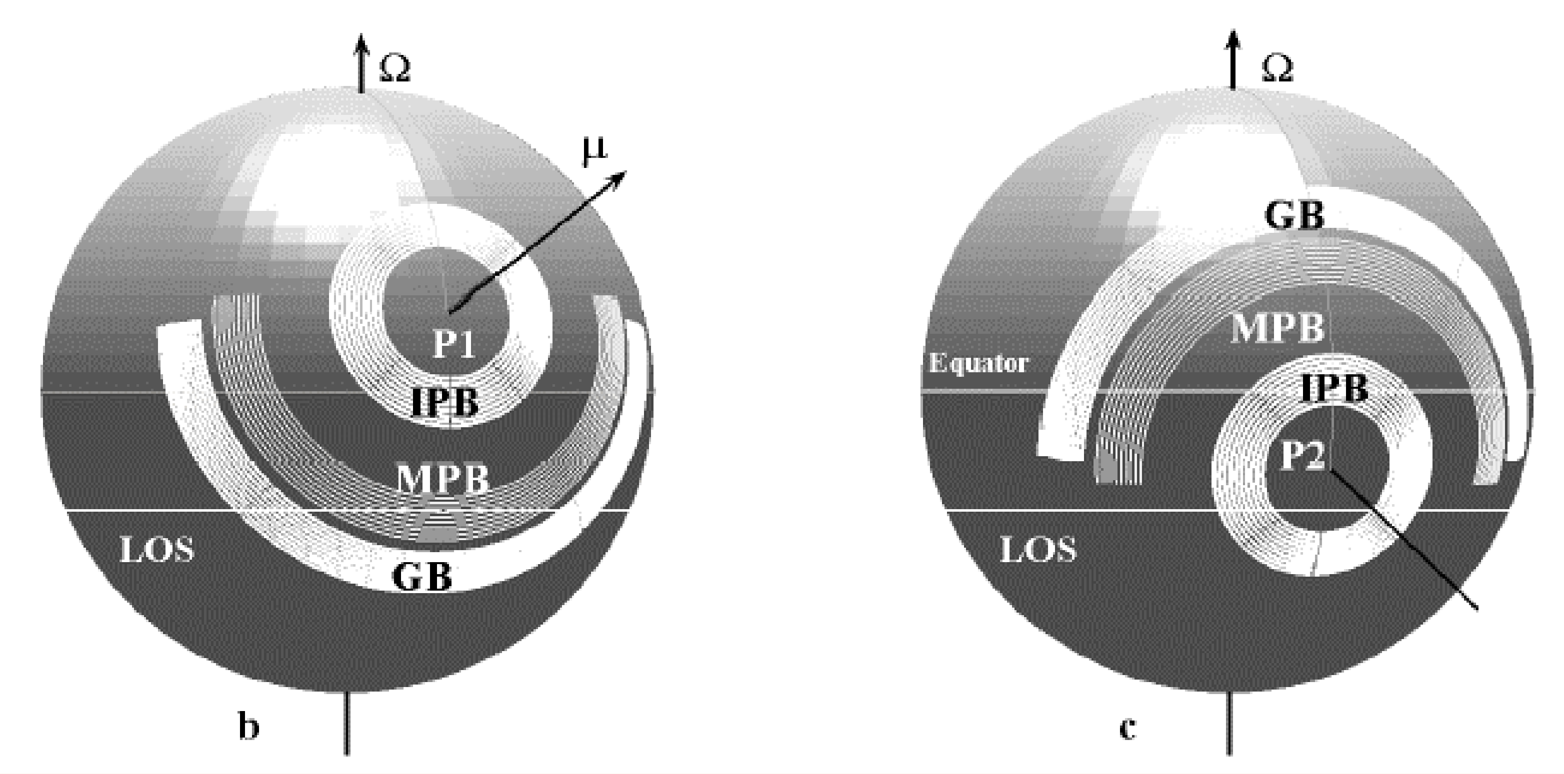
Radio

Gamma-ray



Thompson et al. 1992

Multi-beam observational constraints

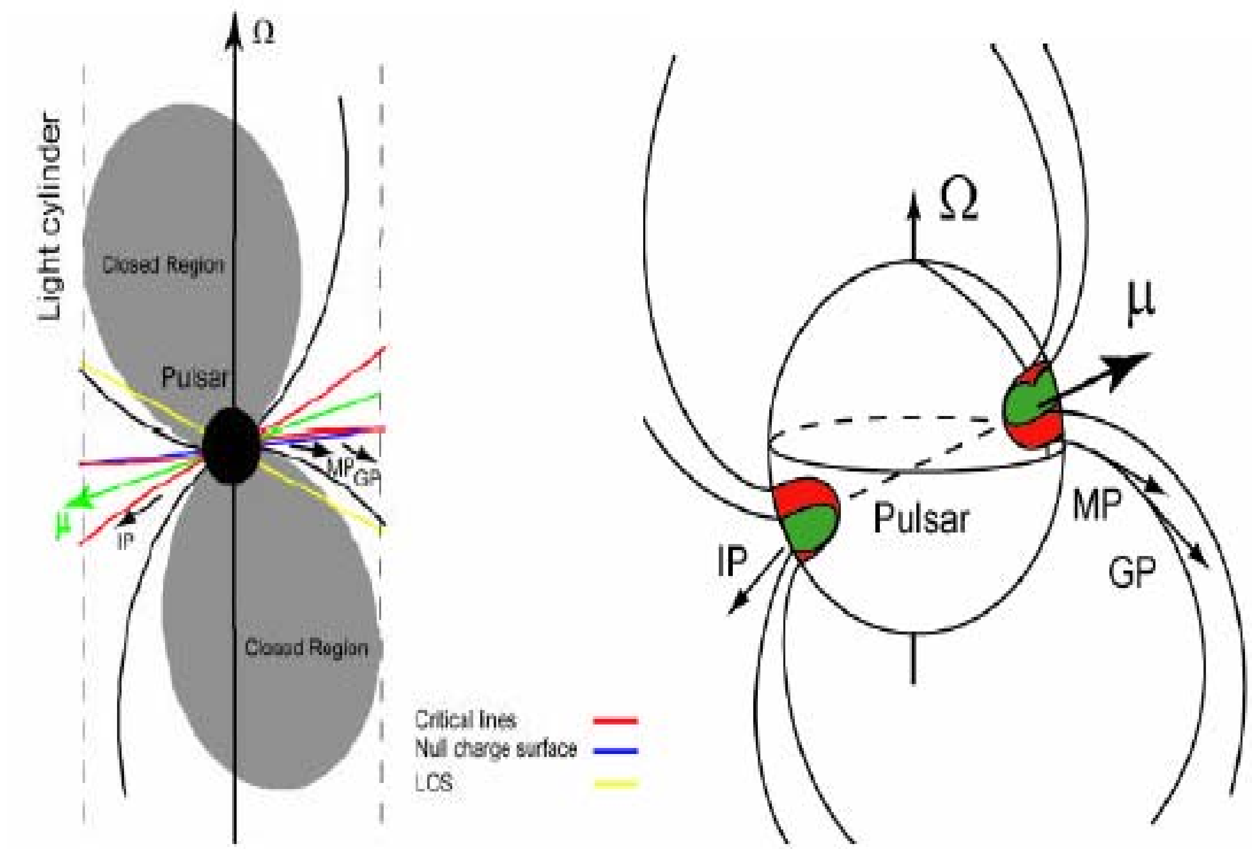


From observation, the radiation location can be determined uniquely for this star.

Wang et al.2006,MN

Annular emission model

The observations show that the radiation position locates in the annular region.



Wang et al.2006

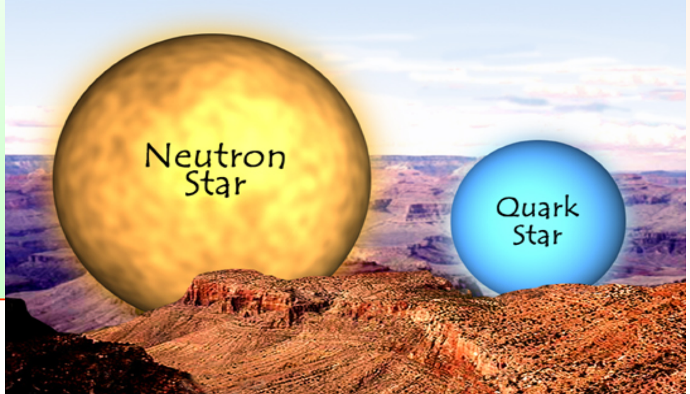
Problems & chance in this field

- **How can we *take a check* for models from observations ?**
- **Are there *gamma-ray millisecond* pulsars?**
- **What is the emission process of the *transient AXP*** ?
- **Can we take a check for *quark star* or NS ?**
- Can we find a ***sub-millisecond*** pulsar?

➔

There is a great chance waiting for us !

(GLAST, FAST)



Cooperators:

Han,J.L. National obs.China

Zhang,B. Dept. of Physics, Univ. of Nevada,USA

Xu,R.X., Dept. of Astr., Peking Univ. China

Lin,W.P., ShangHai Obs. China

Wang,H.G., Guangzhou Univ. China

Lee,K.J., Dept. of Astr. Peking Univ. China

Thank you !

Magnetospere of pulsars

Inner gap

$$V_{max} = \Omega B_s r^2_p / 2c \approx (6.6 \times 10^{12} V) B_{12} P^{-2}$$

Outer gap, α≈1

$$V_{max} = \alpha \Omega B_s h^2_p / cr \approx (6 \times 10^{14} V) B_{12} P^{-3/2}$$

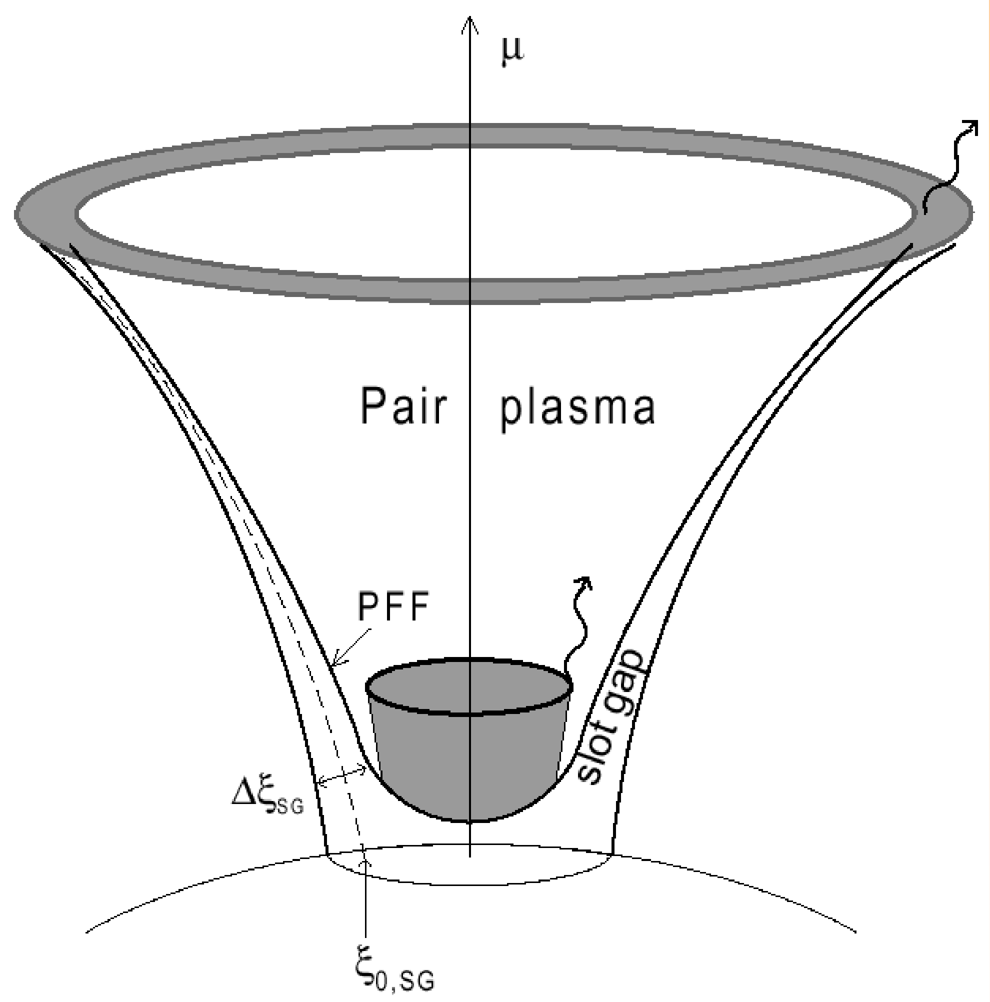
Space charge limited flow

$$dE_{\parallel} / dZ = 4\pi (\rho - \rho_{gj})$$

$$V_{max} = (4 \times 10^{11} V) P^{-1} B_{12} (A/2Z)$$

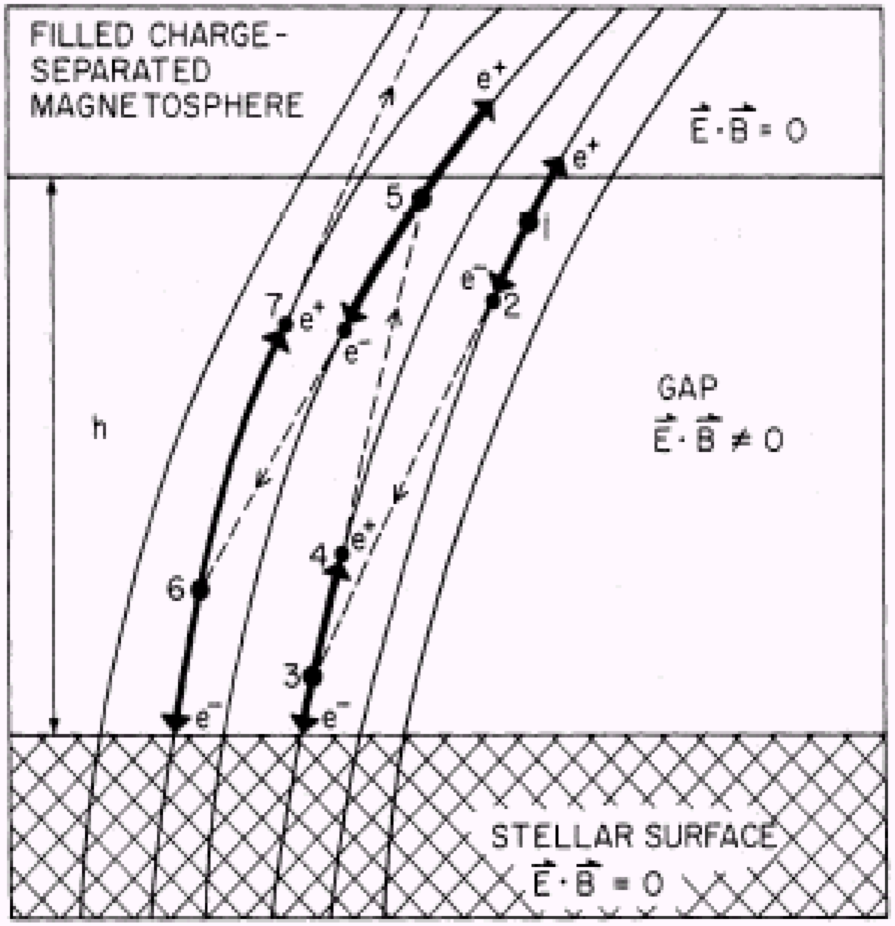
Am--mass of ion, Z-charge of ion

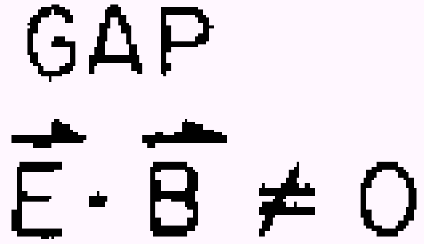
Slot gap model



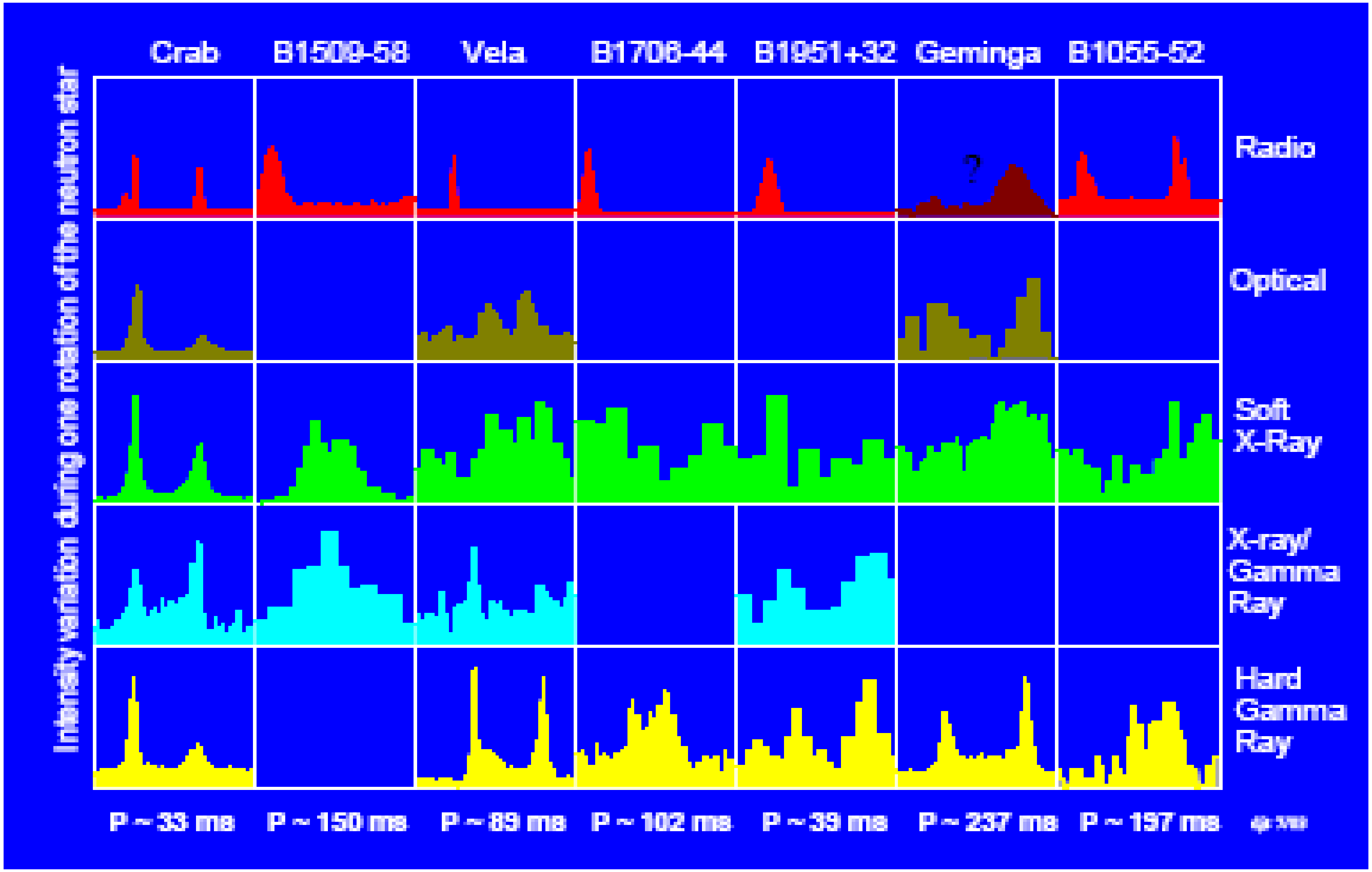
Muslimov & Harding, 2003

ICS model: inner gap sparking $\rightarrow \omega_0$

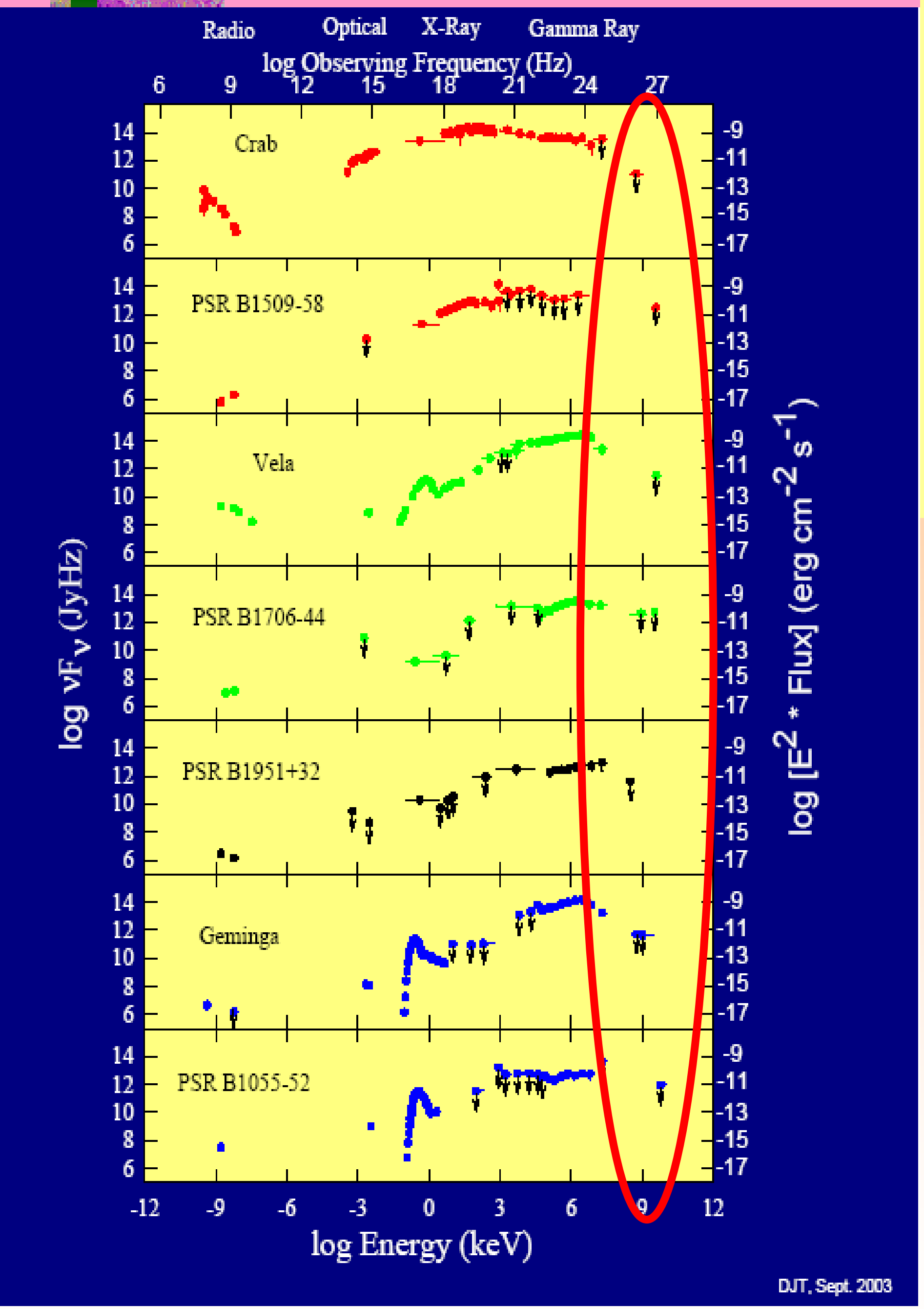




Basic Observational facts



David J. Thompson:astro-ph/0312272



1. **For inner gap**
   1. **Phase resolved spectrum, bridge is hard**
   2. **1e1~1e3 Gev cut-off**
2. **For outer gap**

   Wide beams

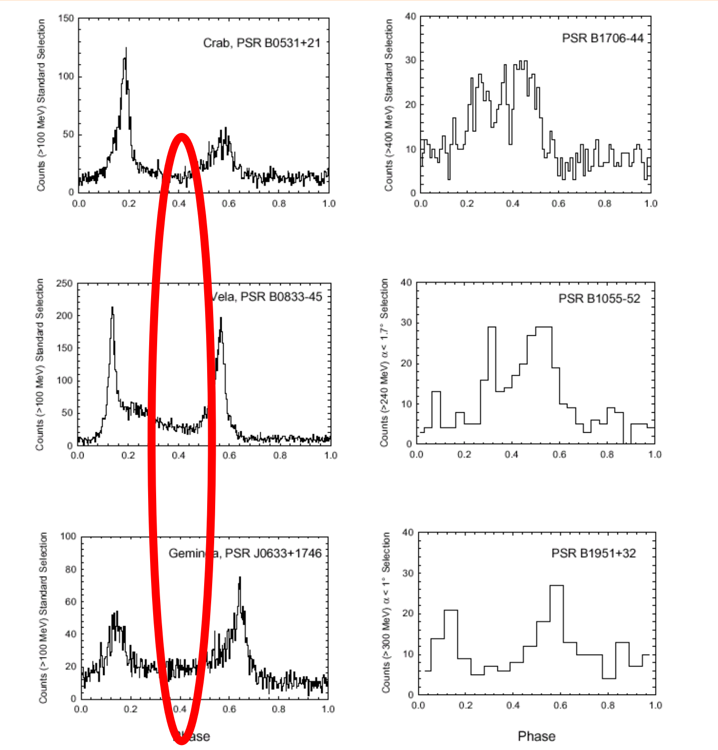


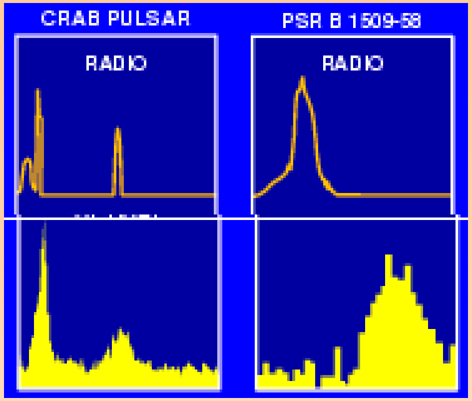
Fig. 2. High-energy light curves of γ-ray pulsars (> 100 MeV, unless indicated differently)

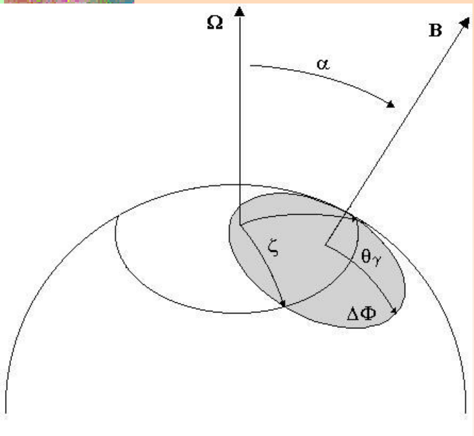
Thompson, astro-ph/0312272 , Kanbach, 2002,astro-ph/0209021

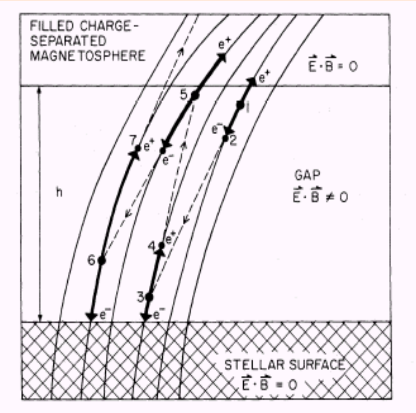
Basic Observational facts vs Theories

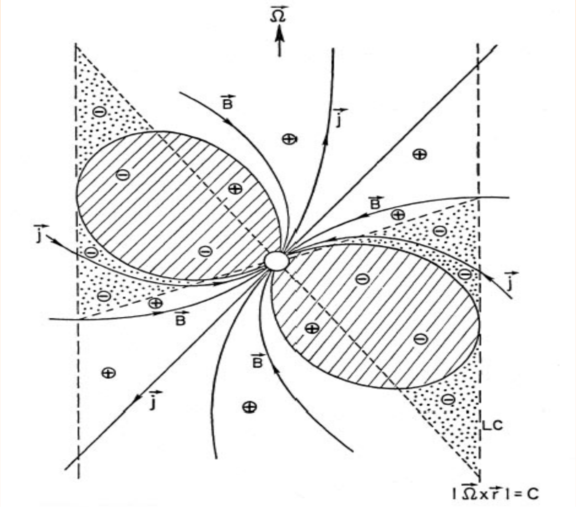
☆**Radio--- Gamma-rays:**

Obs.









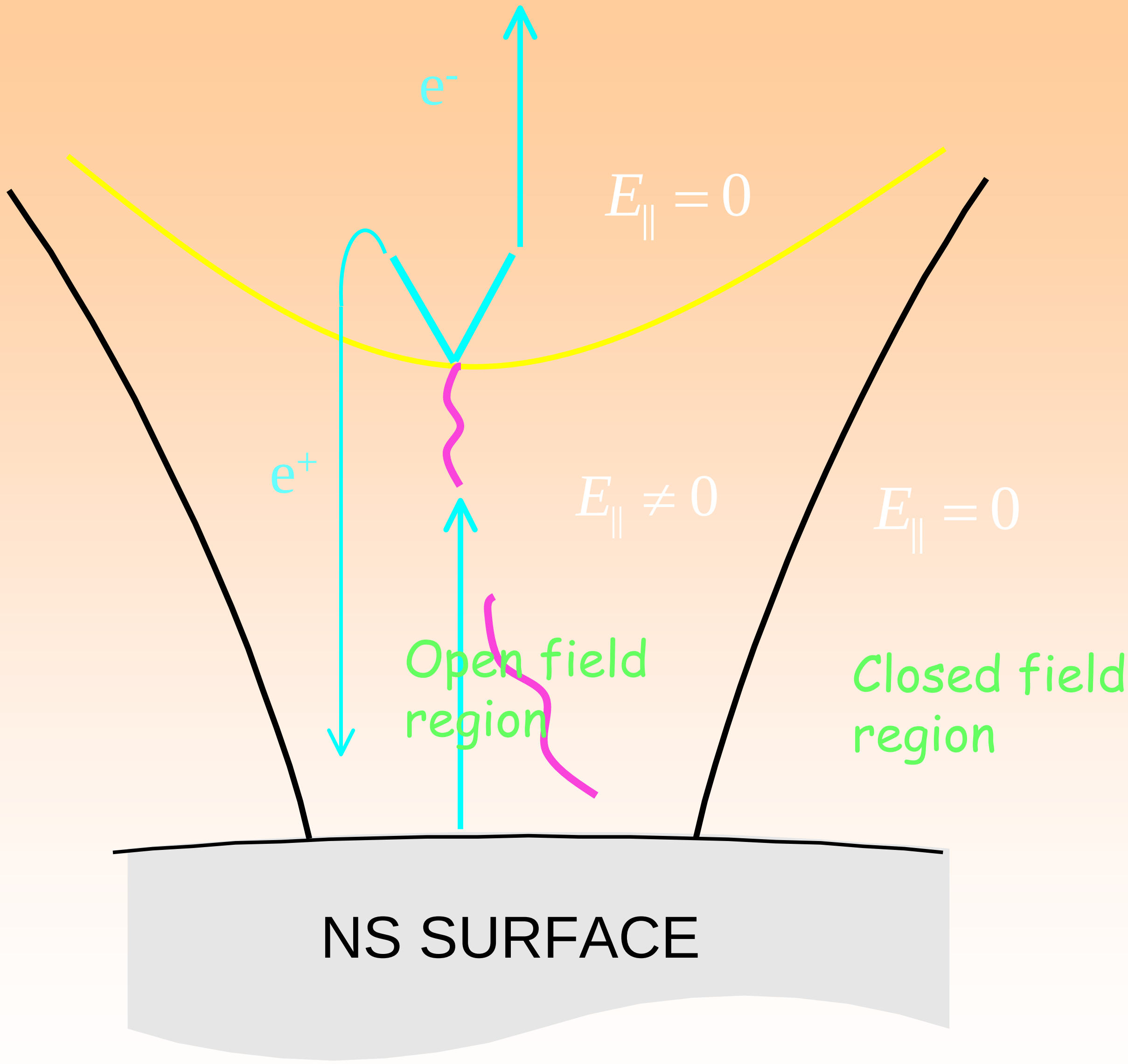
Polar cap (gap)

(Harding, 1981; RS, 1975)

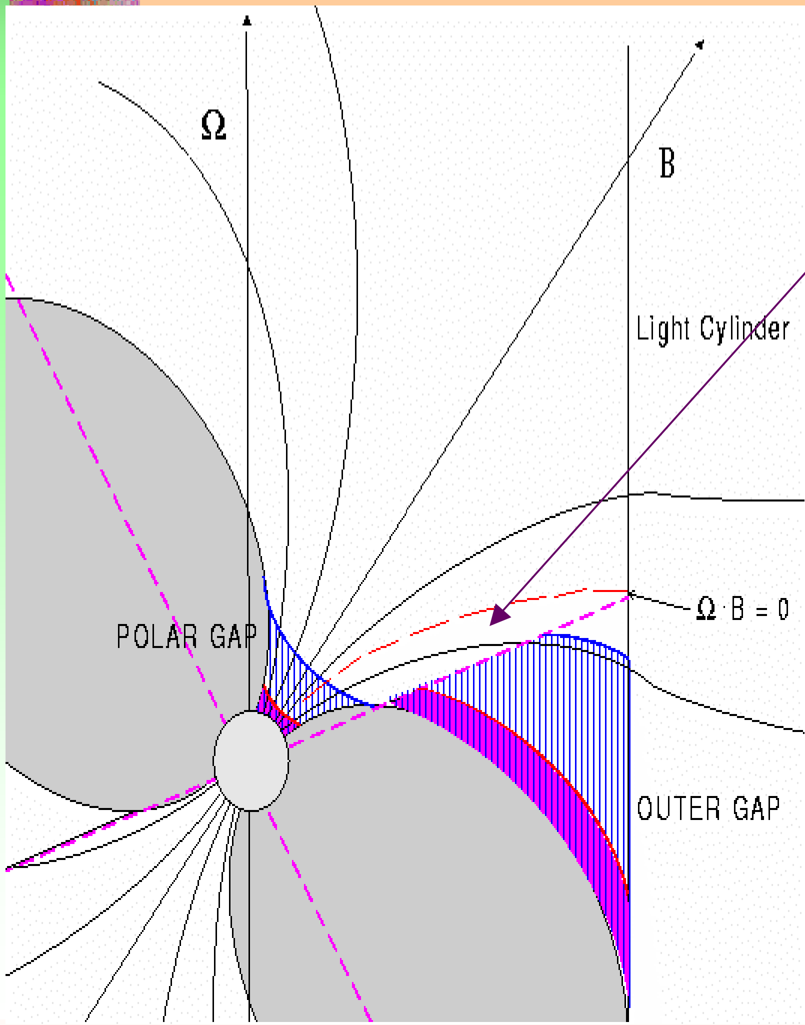
Outer gap

(Cheng et al. 1986)

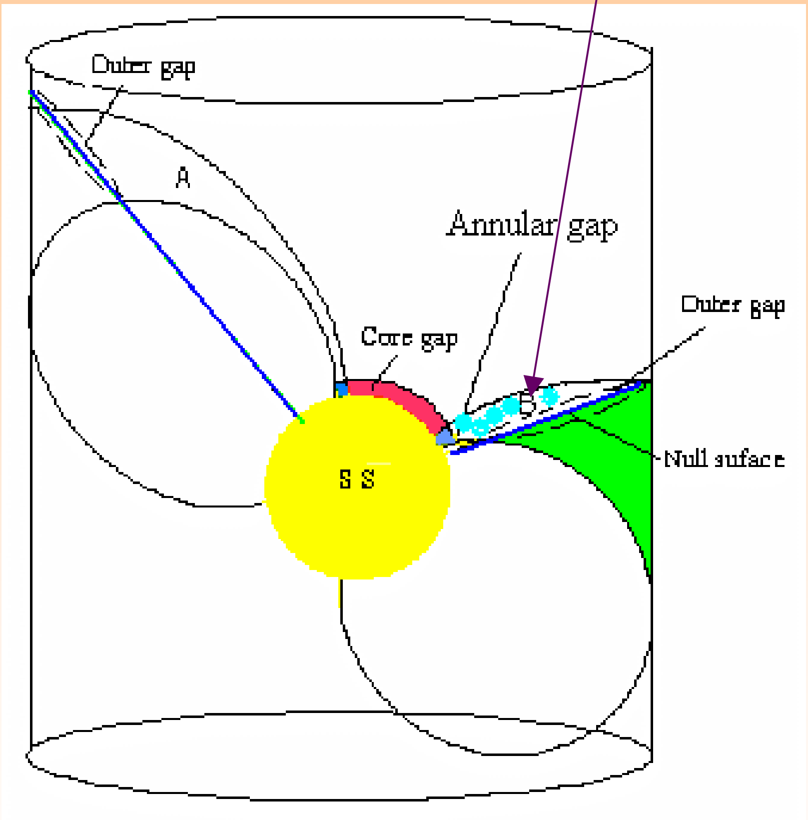
Polar Cap Pair Formation Front



The annular gap

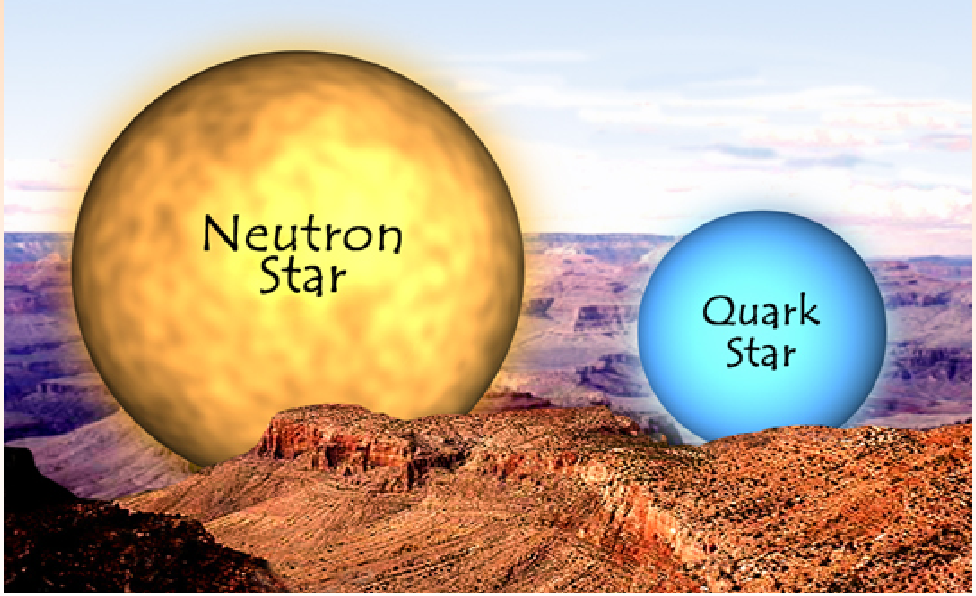


The annular regions

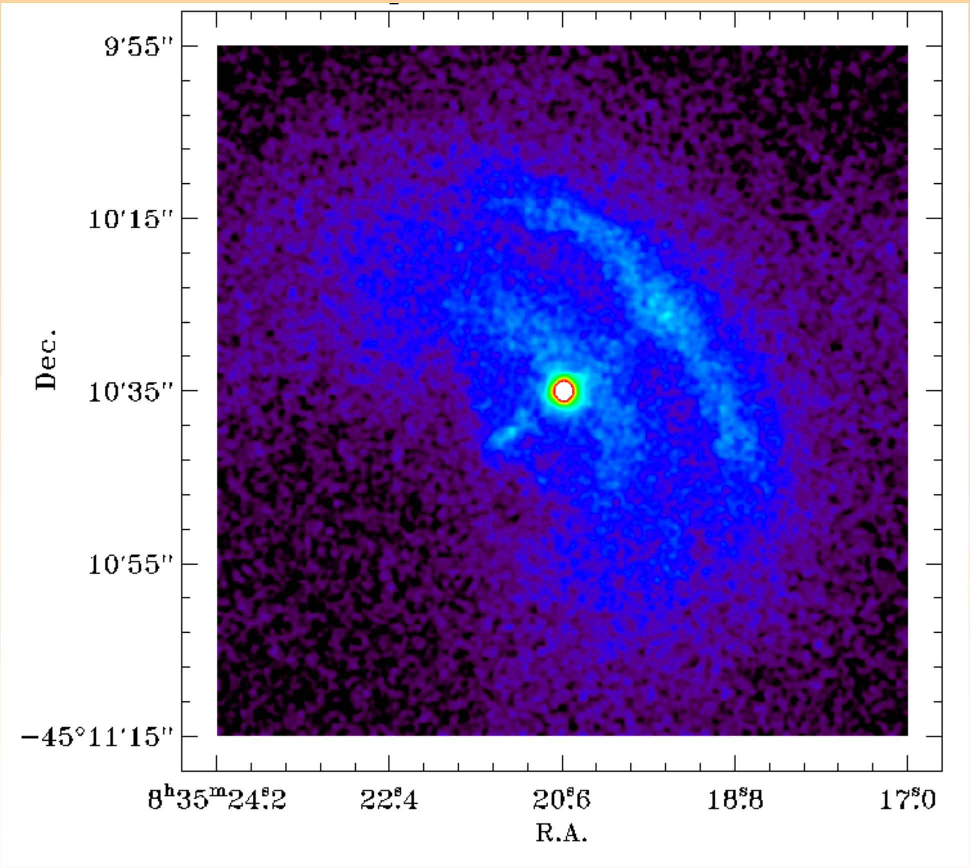


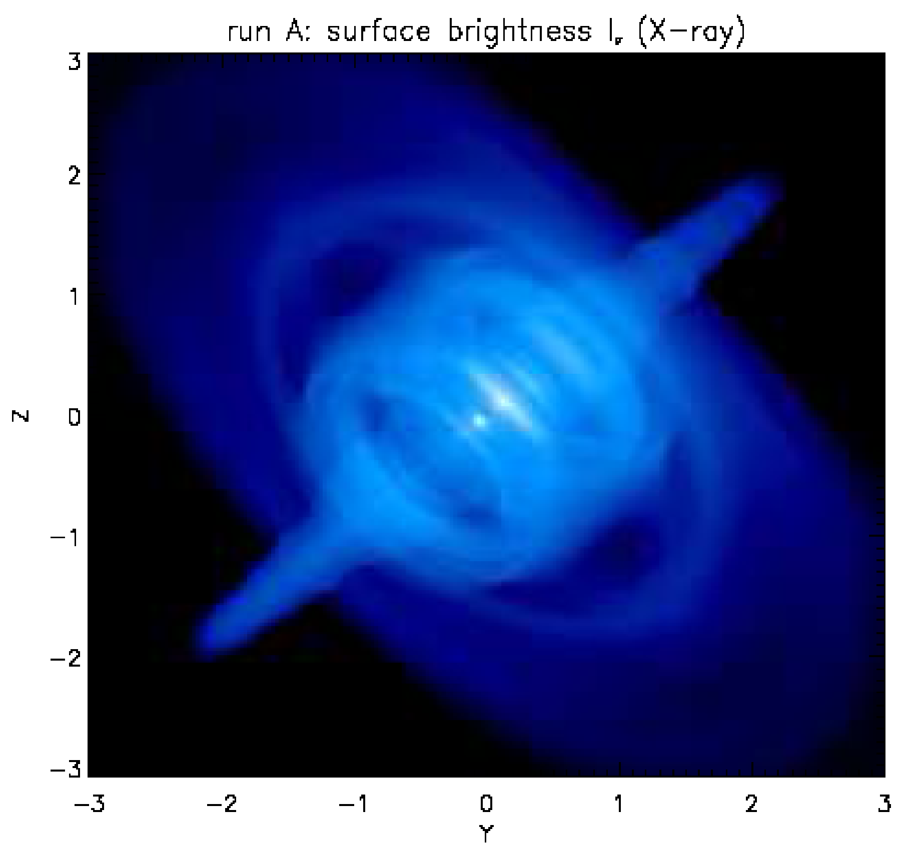
Future obs. & theories

- Pulsars: ***NS or Quark stars*** ?
- Free flow: ***sparking or not*** ?
- Free flow: can produce ***drifting*** sub-pulse?
- Annular gap & others: ***Obs. Test***?



Chandra resolves the **Vela pulsar** from its pulsar wind nebula



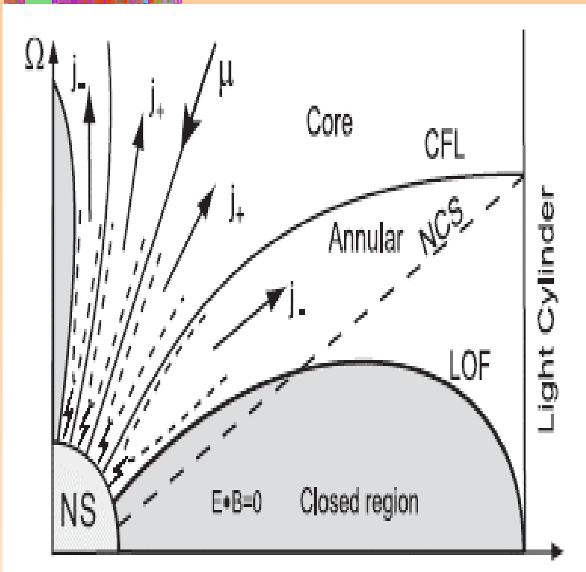


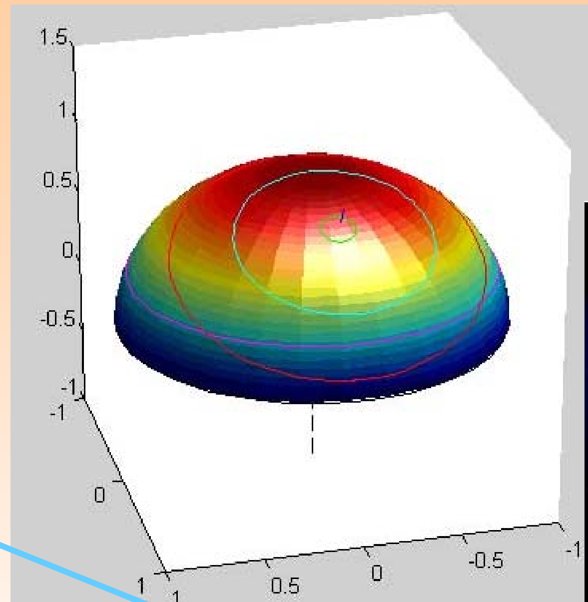
The PWN axis inclined by 30 degree, with respect with the plane of the sky and of 48 degrees. To compare with images of the Crab Nebula.

Arons,2007

Qiao et al.2004,2007

Two particle beams?



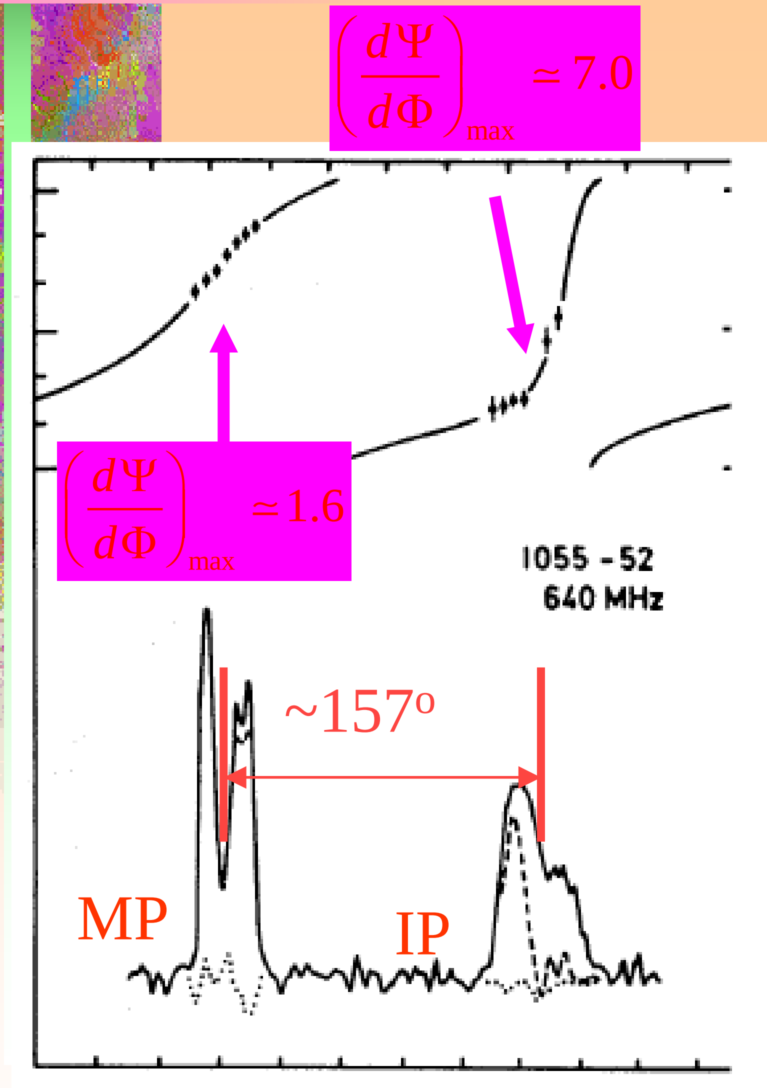


?

PSR B1055-52 :

observational constraints

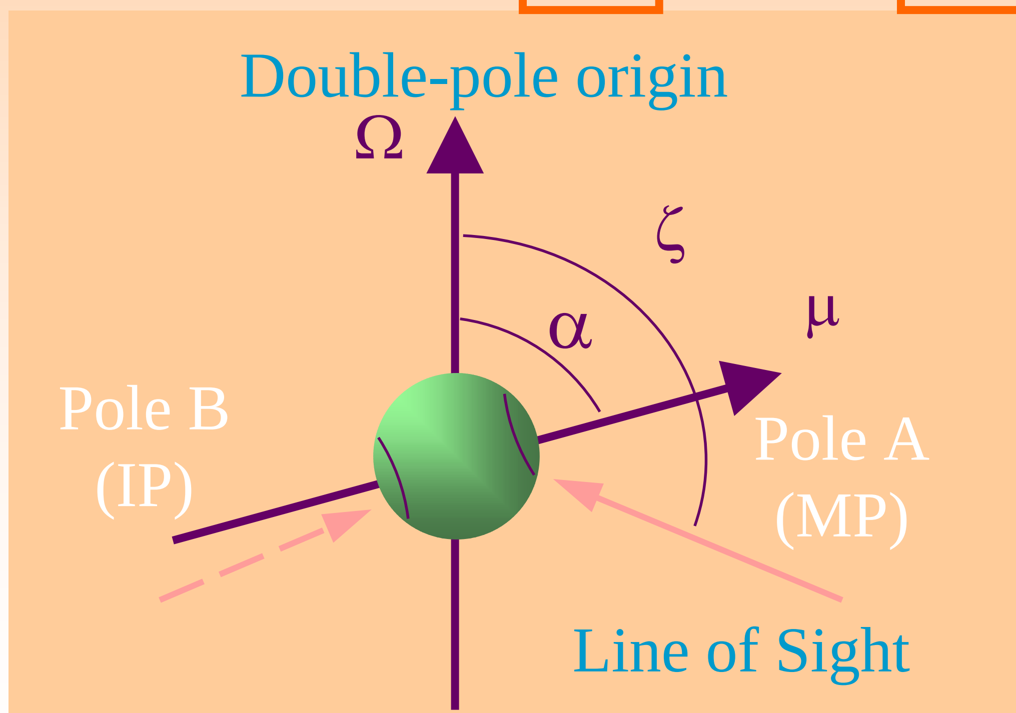
Position angle sweep fit with Rotation Vector Model



Lyne & Manchester 1988

Inclination Angle α Viewing Angle ζ

Authors	Frequency (MHz)	α (°)	β_{MP} (°)	β_{IP} (°)	ζ (°)
LM88	640	74.7	38.7	-7.9	113.4
Ommen et al.	950	78±5	33	-9	111

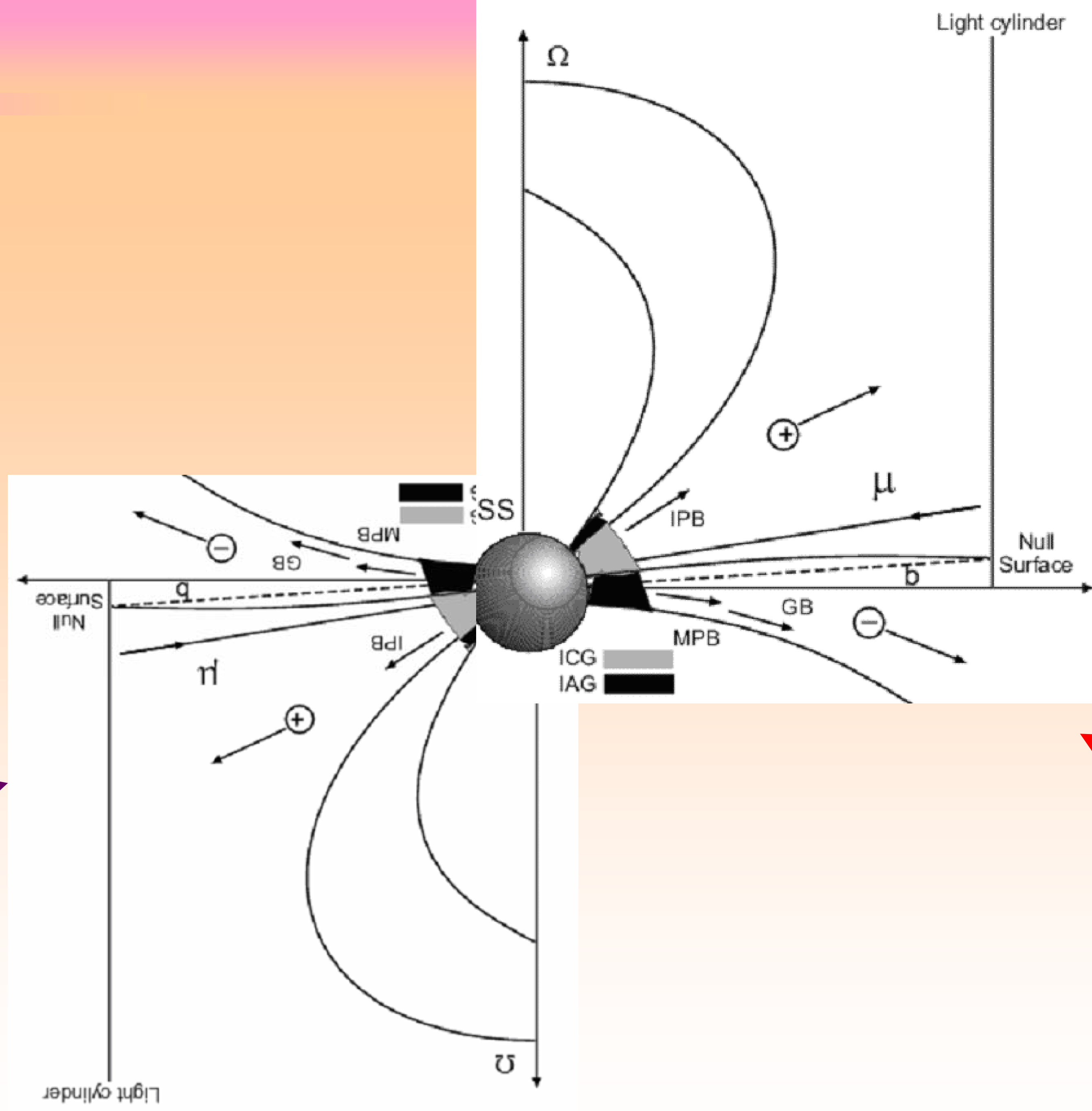


Wang et al.2006

PSR B1055-52 :

Multi-beam observational constraints

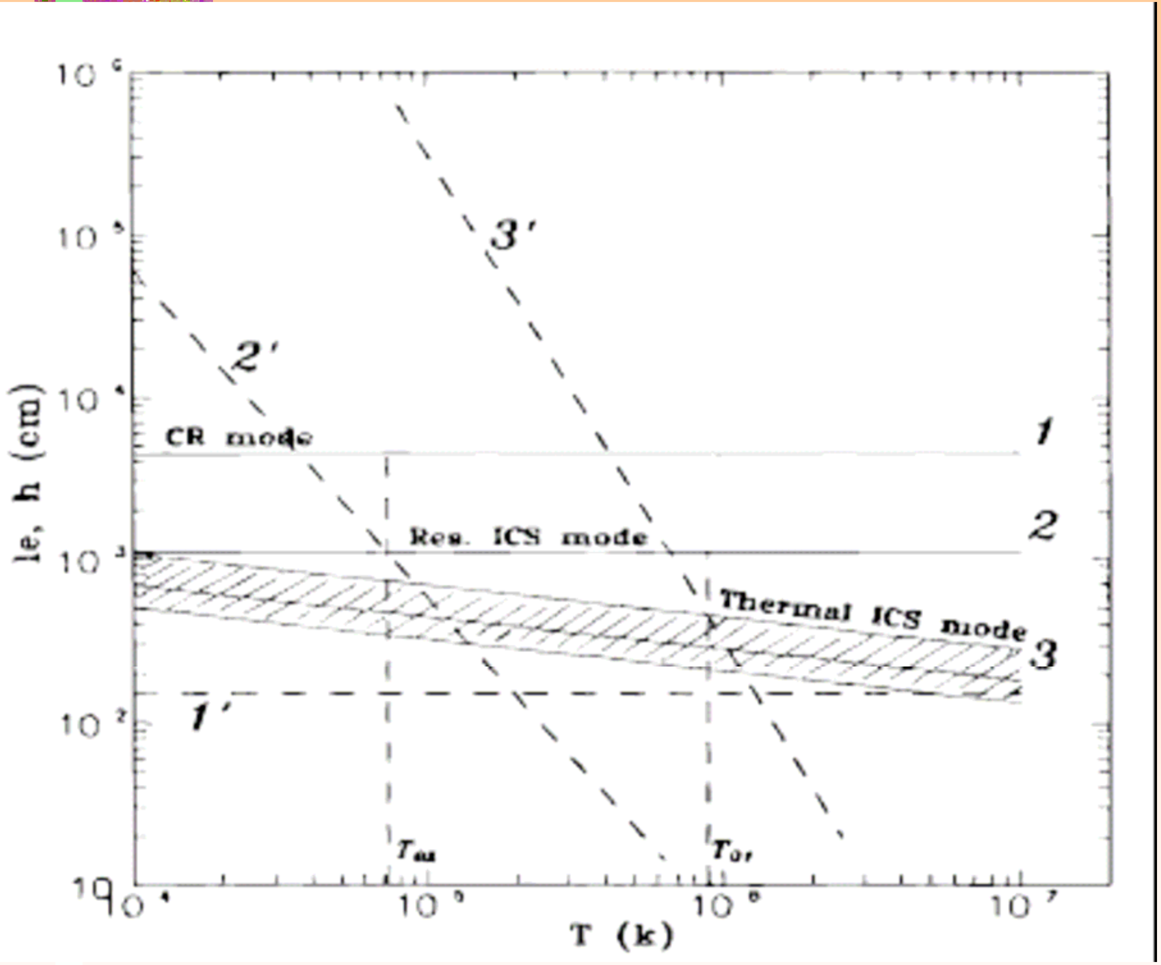
- 1). Inclination angle
- α=74.7 degrees
- 2). Viewing angle
- ζ =114 degrees



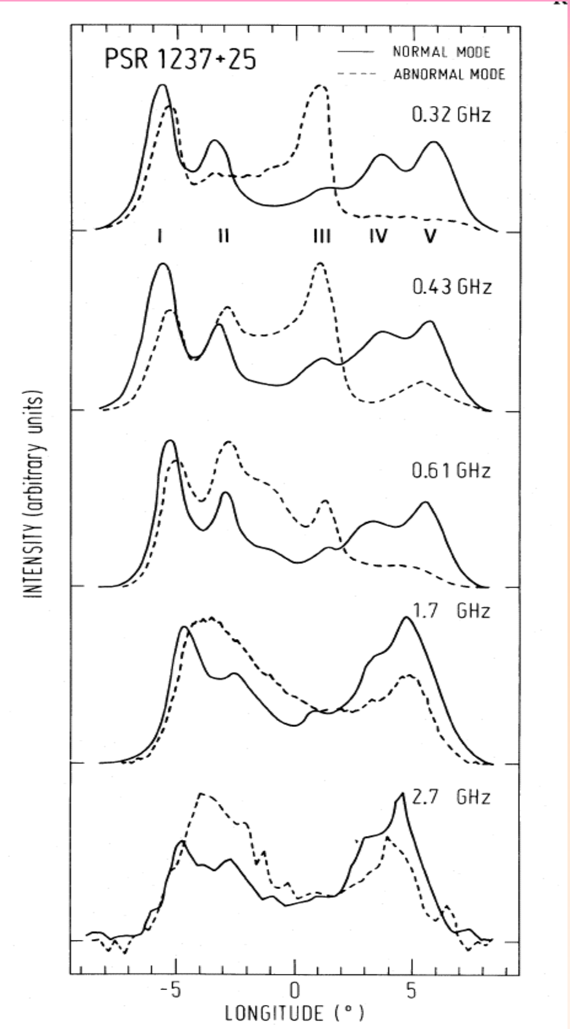
Obs.

Obs.

Mode changing



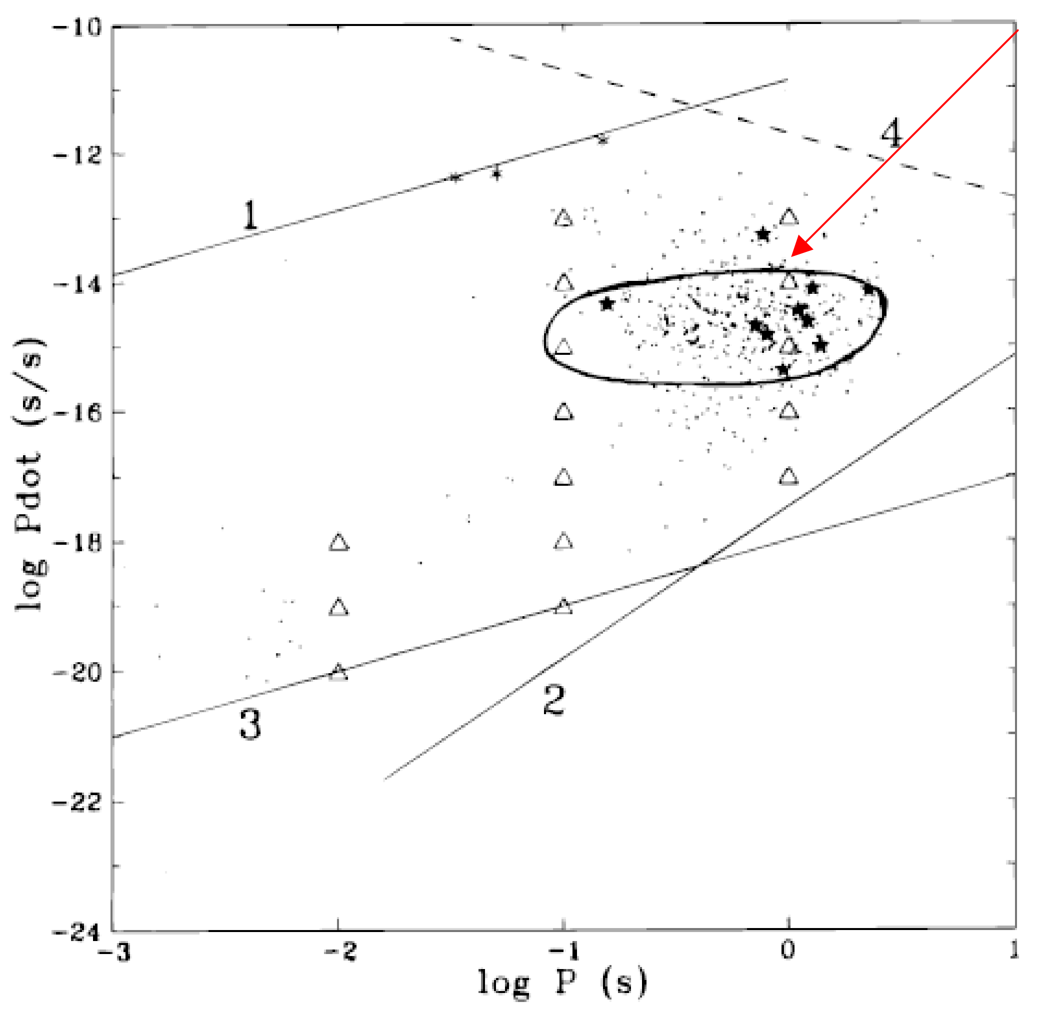
Zhang,Qiao,Lin,Han, 1997



Rankin, 1986

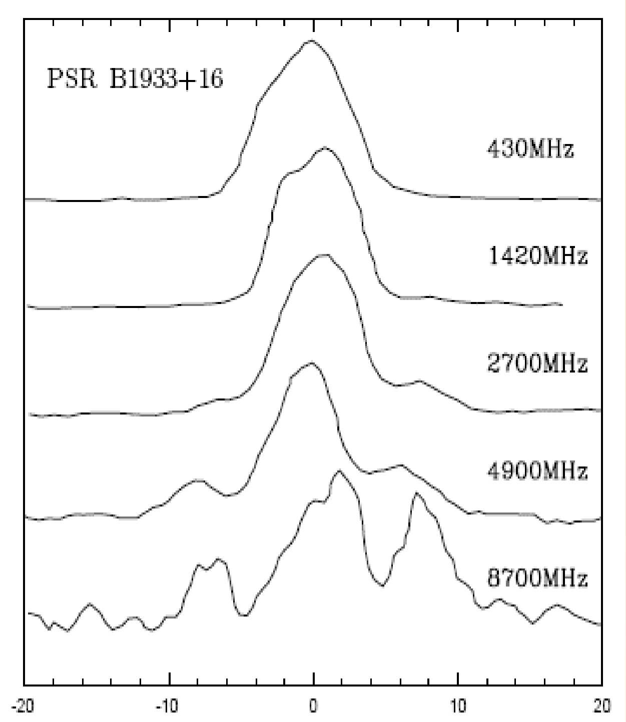
Mode changing

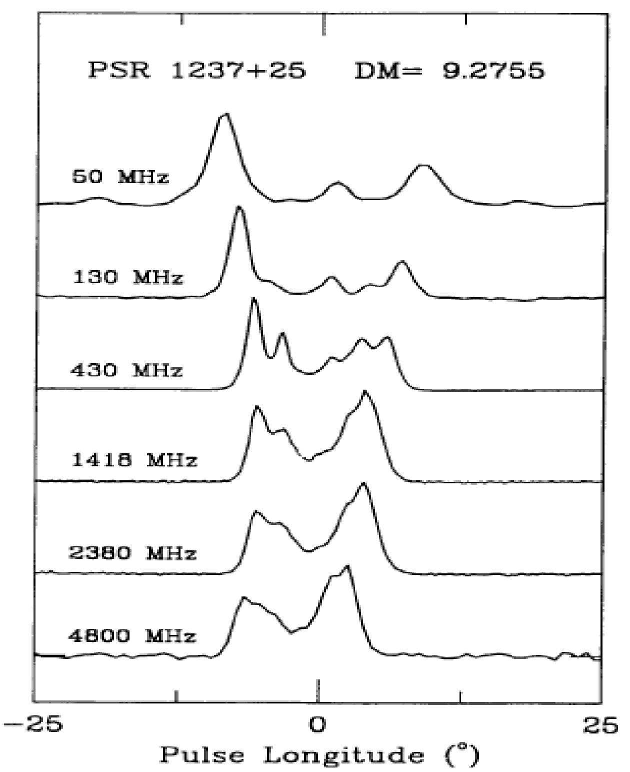
Mode change pulsars

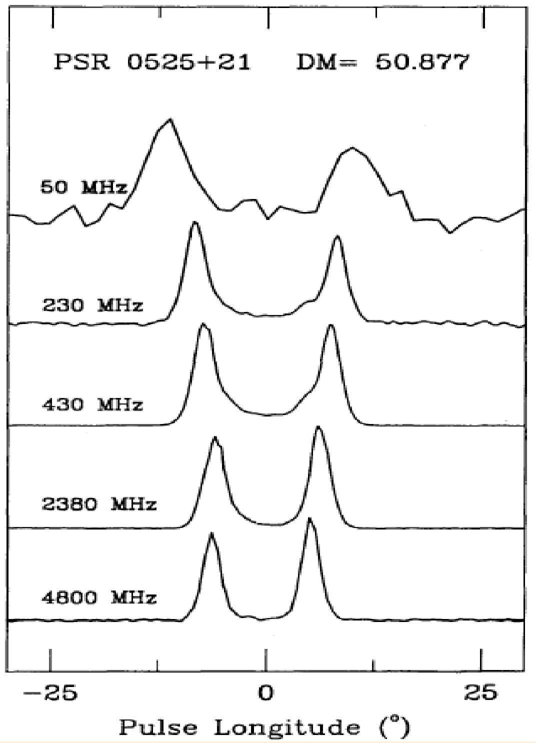


Zhang,Qiao,Lin,Han,1997,ApJ
Zhang,Qiao, Han, 1997,ApJ

Pulse profiles: changing with frequencies





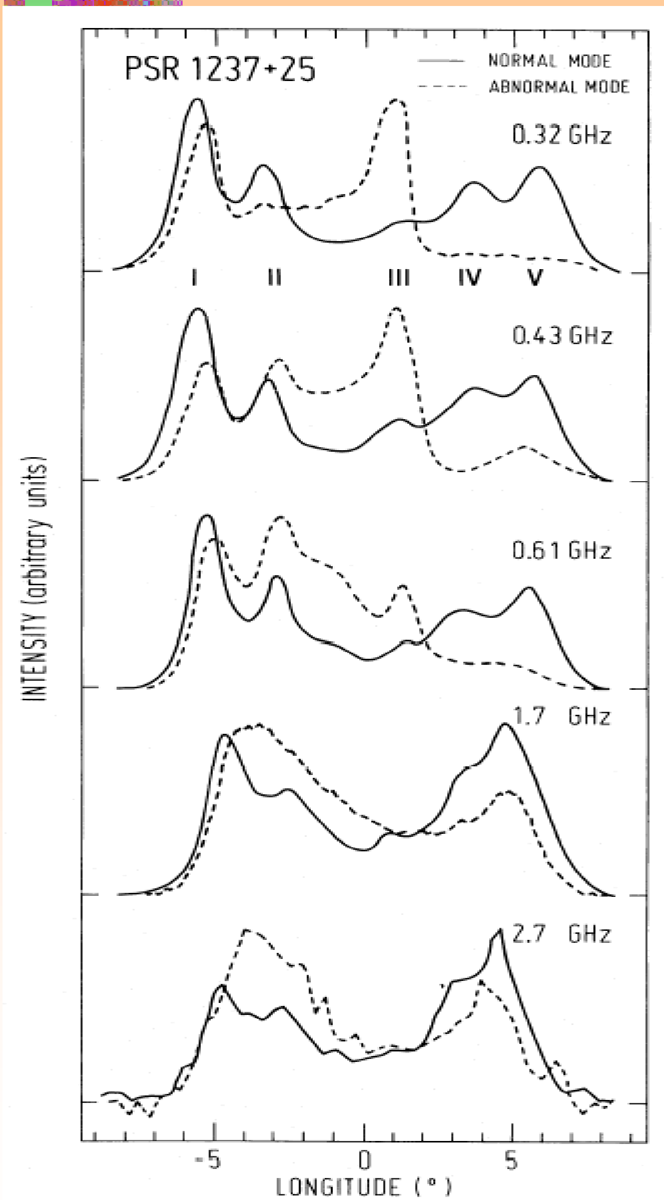


High frequencies:
wider,
Core beam.

Low frequencies:
wider,
Core beam, conal beam

Low frequencies:
wider,
Conal beam only.

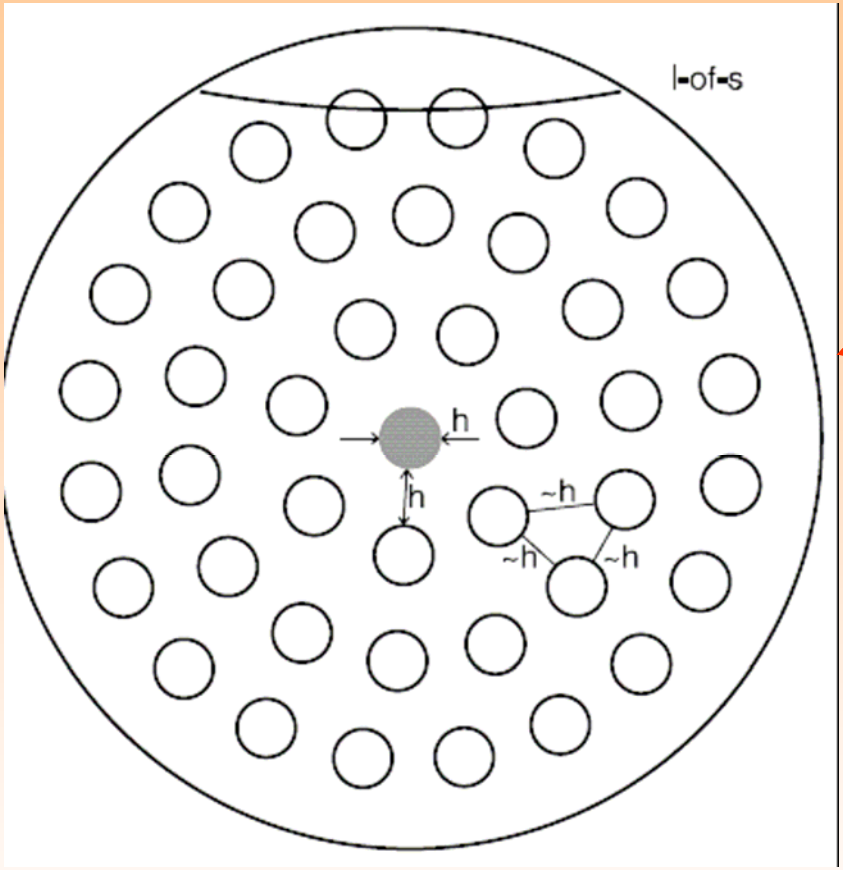
Mode changing



Normal mode to abnormal mode: less than a period

Rankin, 1986

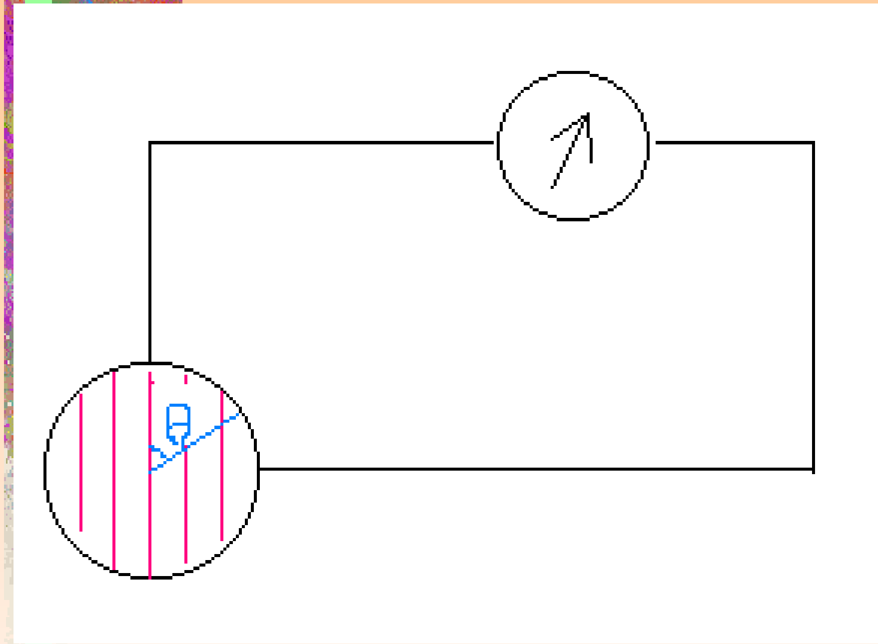
Spark Model



Polar cap region

Gil & Sendyk, 2000

Mono-generator



$$E = B_s \Omega R^2 \sin^2\theta / (2c)$$

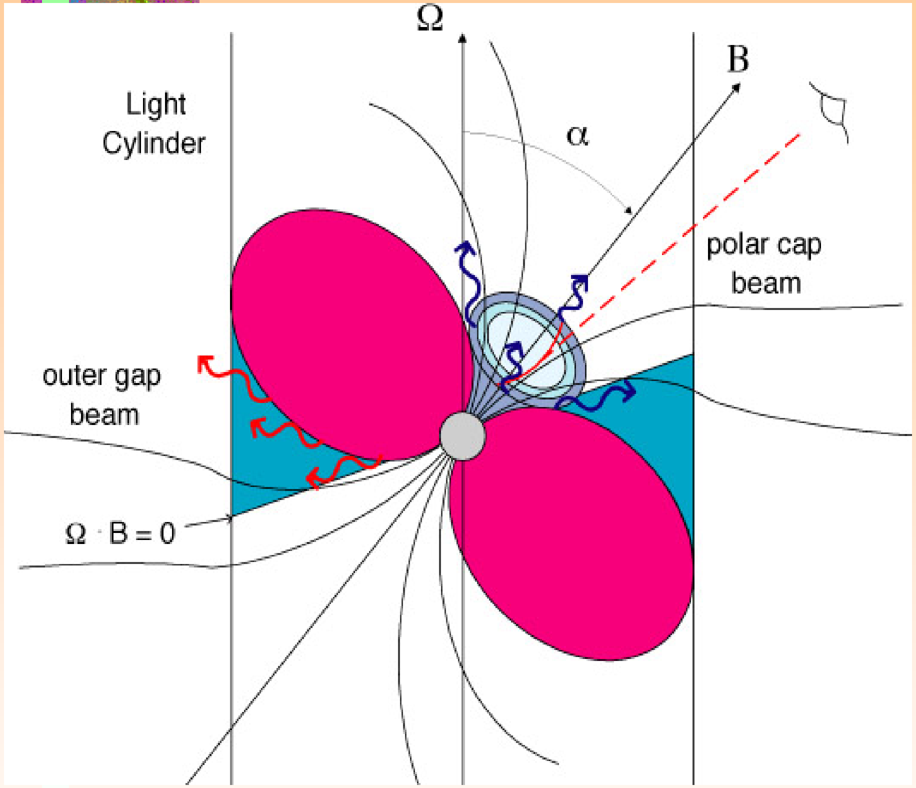
For the Sun:

$$E_{max} = 10^7 V$$

For Crab Pulsar:

$$E_{max} = 10^{18} V$$

Pulsar acceleration regions



- Pulsars are **broad-band** emitters (gamma-ray, X-ray, optical, radio)
- Pulsars must be **particle accelerators**
- Three preferred acceleration regions:

--- ***Polar cap*** region

--- ***Outer gap*** region

--- ***Annular gap*** region

Where the particles can be accelerated?

$$\rho - \rho_{GJ} \neq 0 \quad \rightarrow \quad E_{//} \neq 0$$

1. Gap: *inner gap* & *outer gap*
2. Space Charge Limited Flow:
   Polar cap; Slot gap
3. *Annular gap*