PULSAR ELECTRODYNAMICS

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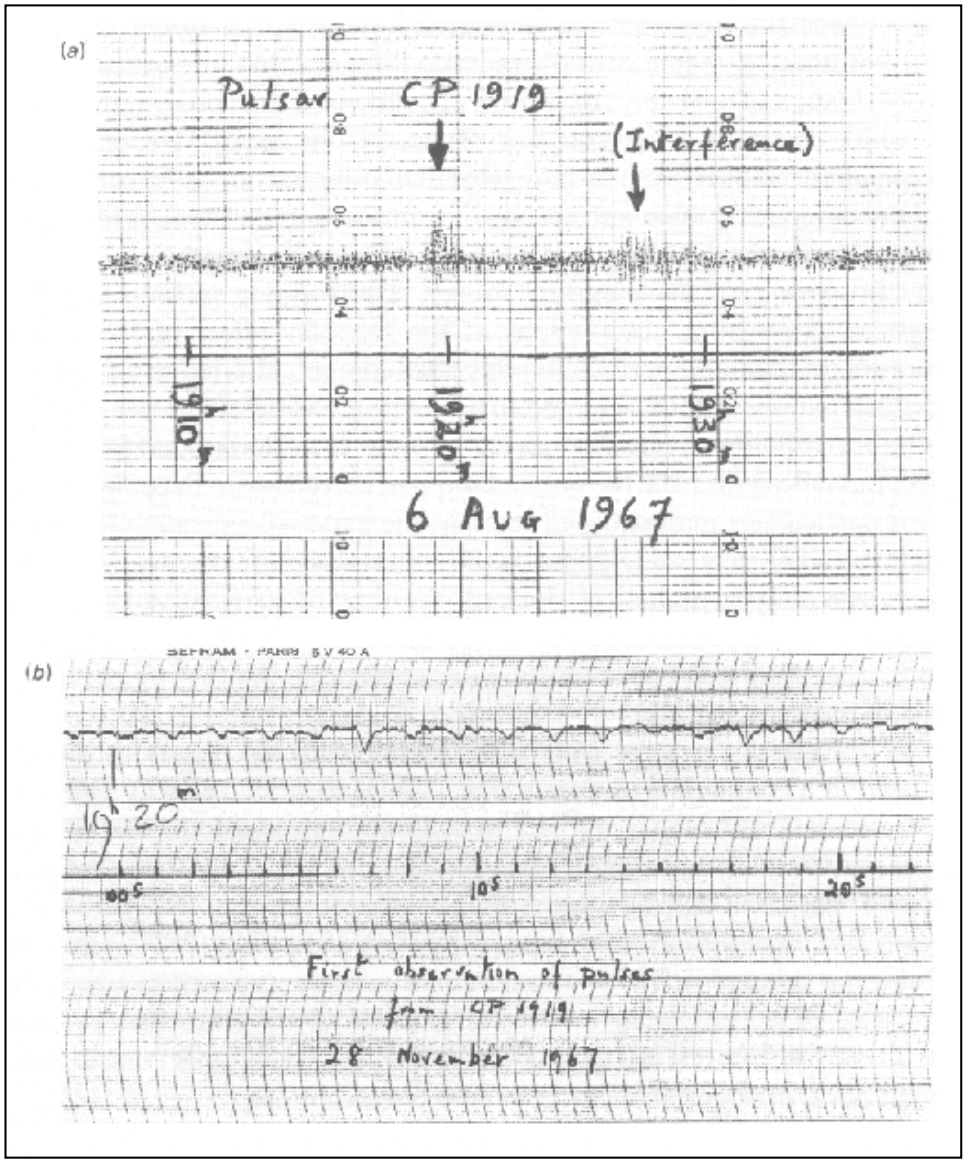
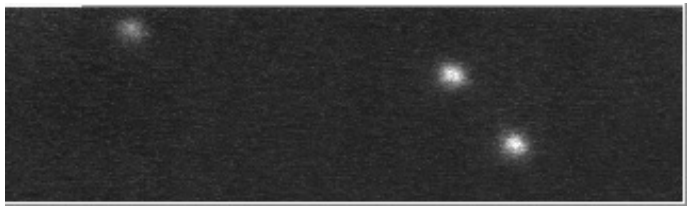
Pulsar ABC



- First discovery: PSR B1919+21, November 28, 1967, by Jocelyn Bell Burnell and Antony Hewish.
- 1974 Nobel Prize

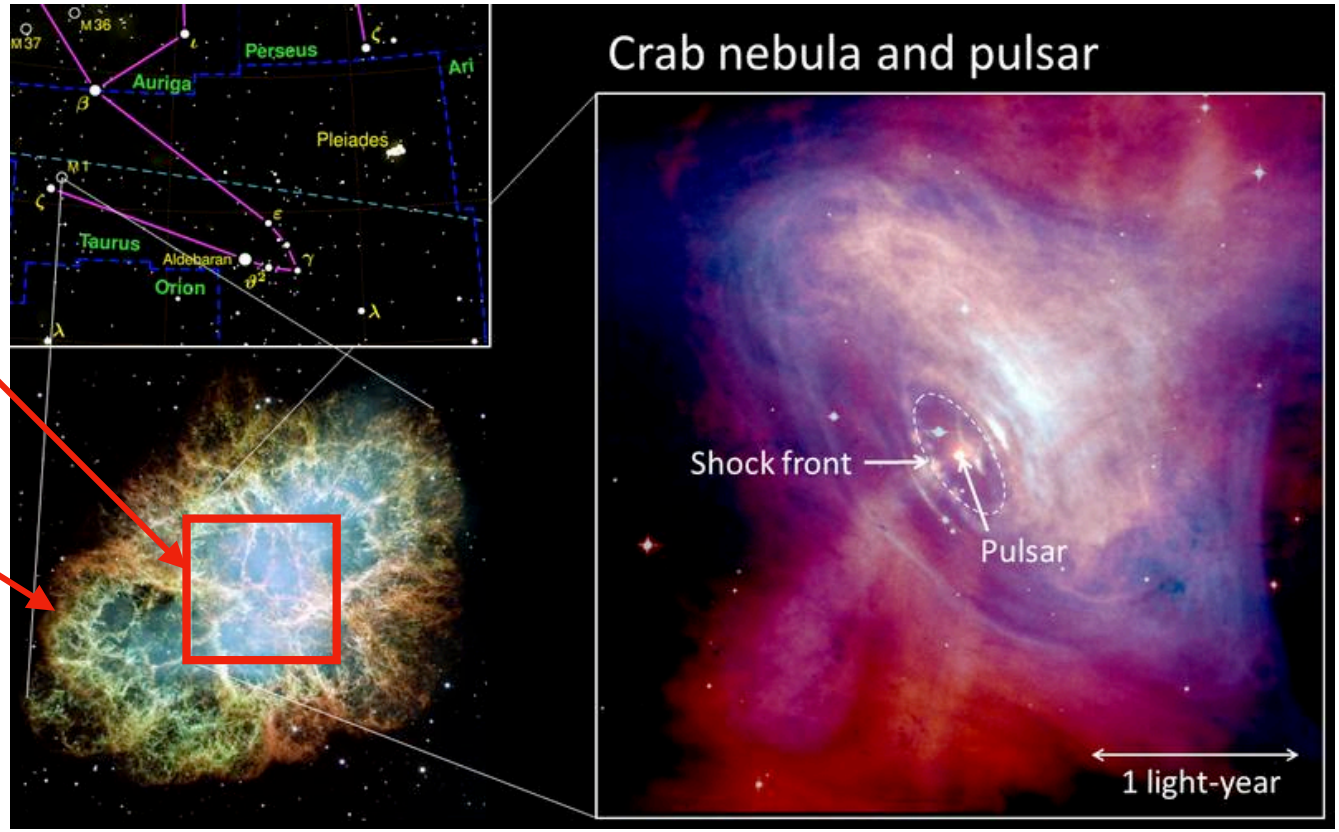
Pulsar ABC

- **Pulsar Formation & Structure**
  - Supernova -> neutron star -> pulsar



Pulsar Wind Nebula

Supernova Remnant

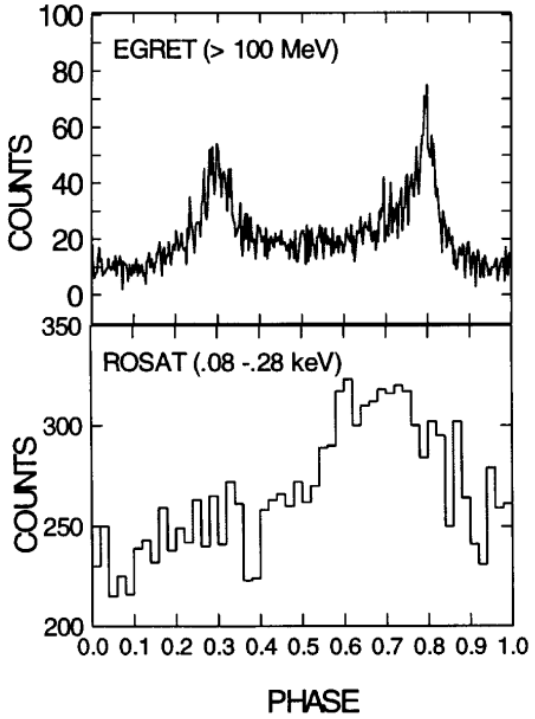


(Hubble & Chandra)

Pulsar ABC

- **Radio & Gamma Ray Profile**

Geminga



(Alice K. Harding and Alexander G. Muslimov, 1998)

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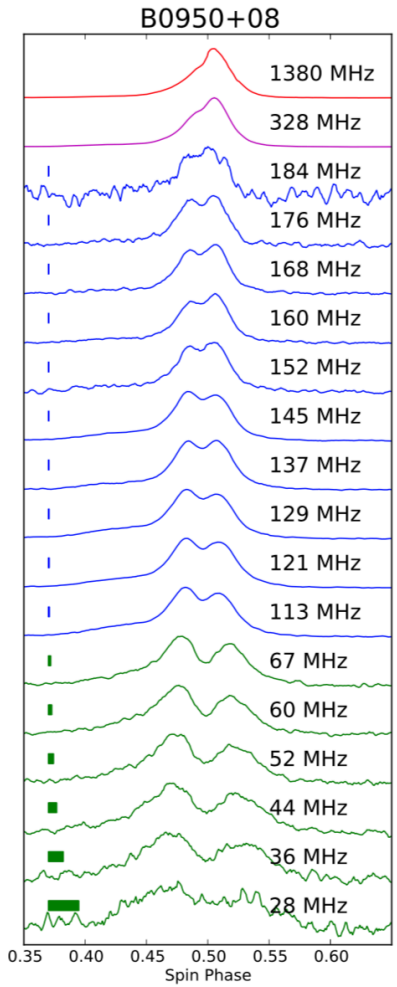
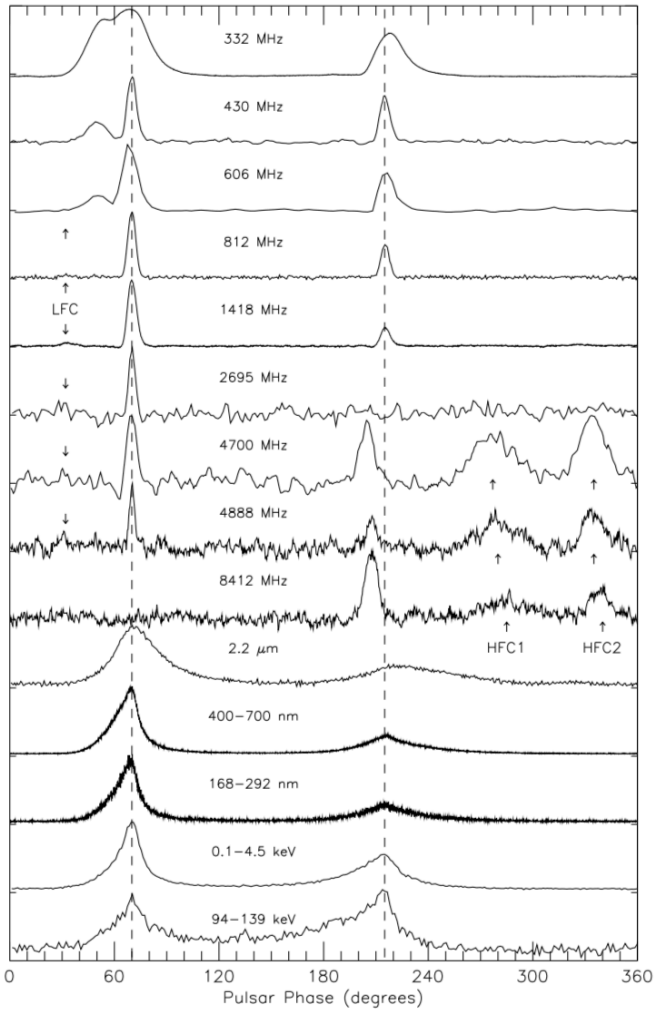


(M. Pilia, J. W. T. Hessels, et.al, 2015)

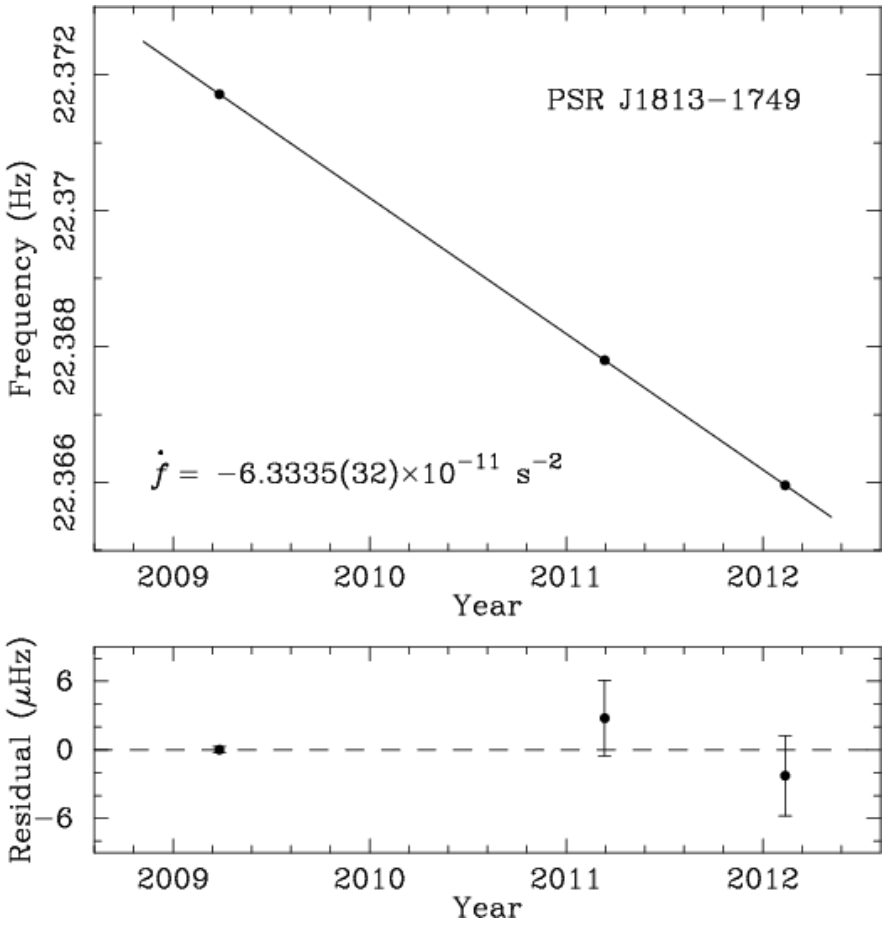
Crab Pulsar



(J. A. Eilek & T. H. Hankins)

Pulsar ABC

- **Spin down and pulsar timing**



(J.P. Halpern, E.V. Gotthelf, F. Camilo, 2012)

Crab Pulsar P = 33.5028583 ms, P' = 3.7e-10 Hz/s

Magnetic Dipole Radiation Power

$$P = \frac{\mu_0 \Omega^4 m_0^2}{12\pi c^3}$$

Estimate Pulsar Radiation Power **or** **Surface Magnetic Field**

Pulsar ABC

- **Motivation: Why Pulsar?**

  The most extraordinary physics laboratories in the Universe

  density, gravity, magnetic and electric fields.

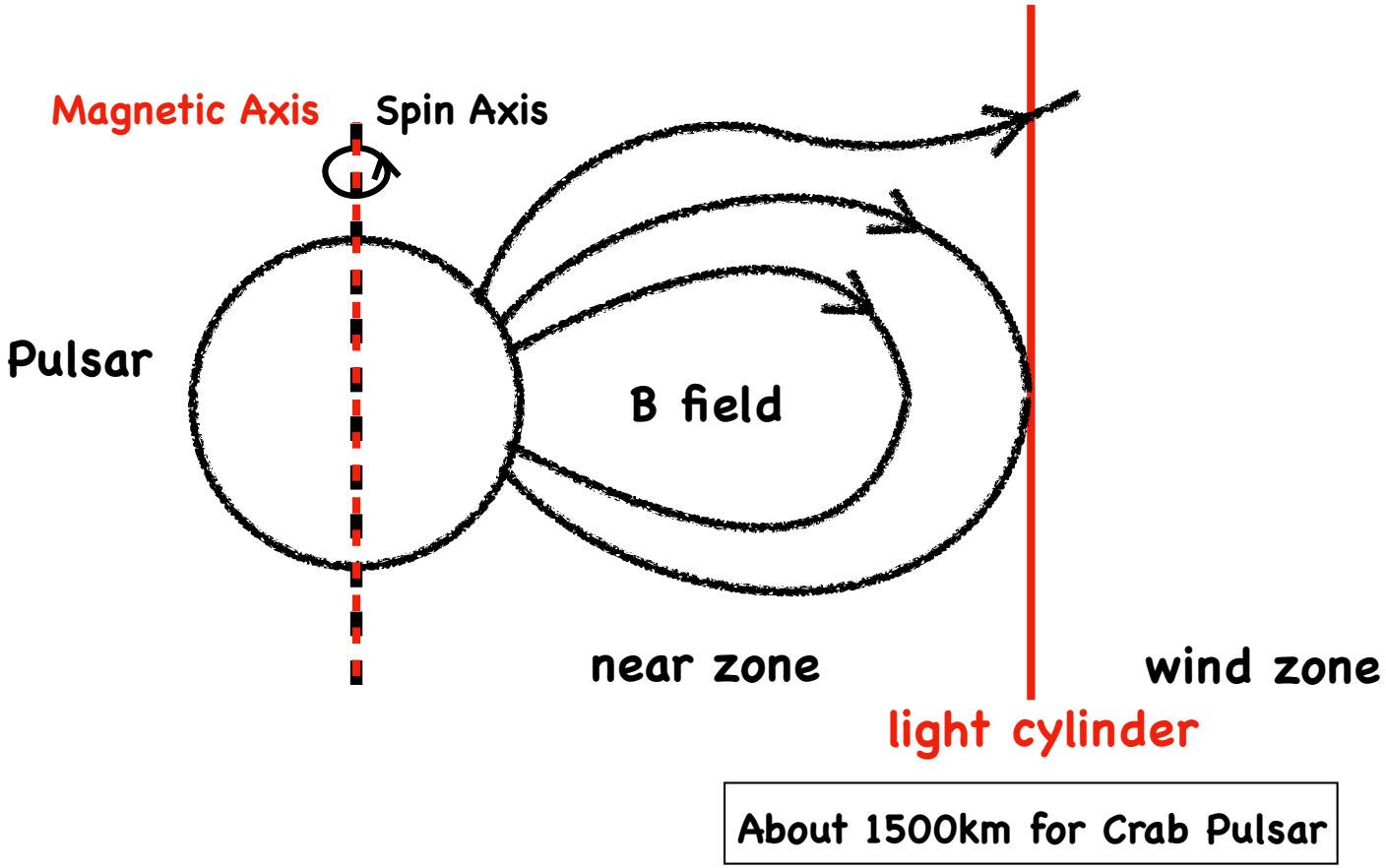
  High Power & Luminosity Radiation

  Open questions like: extreme equation of states, physics of strongly magnetized plasmas, radiation mechanisms, etc.

  Gravitational Waves!

Electric & Magnetic Fields around Pulsar

- **Structure of a Axisymmetric Pulsar**



About 1500km for Crab Pulsar

Electric & Magnetic Fields around Pulsar

- **Outside of Pulsar:**
  - **interior boundary condition**

$$E + \frac{(\Omega \times r)}{c} \times B = 0$$

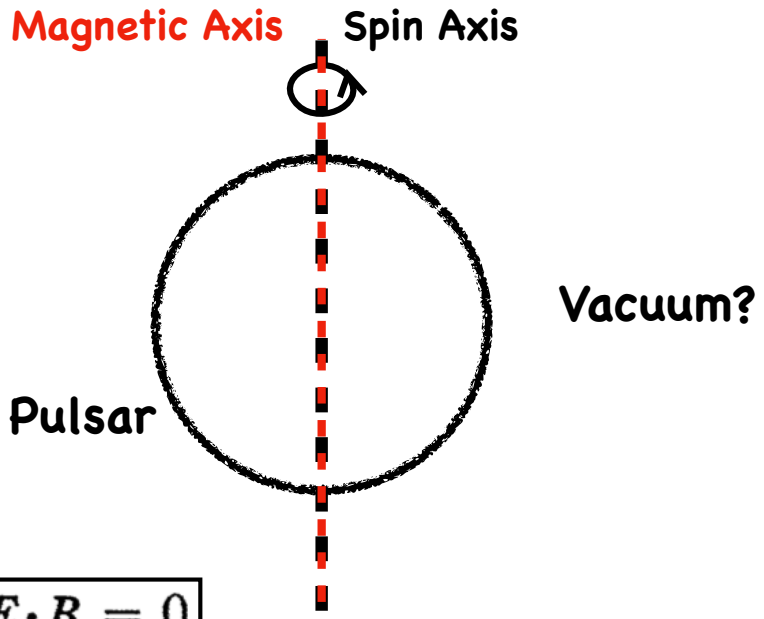
Outer Space Electric Potential

$$\Phi = \frac{-B_0 \Omega R^5}{3cr^3} P_2(\cos\theta)$$

Electric quadrupole induced by the Magnetic dipole

$$E \cdot B = -\left(\frac{\Omega R}{c}\right)\left(\frac{R}{r}\right)^7 B_0^2 \cos^3\theta$$

$$E \cdot B = 0$$



(Peter Goldreich & William EL Julian, 1969)

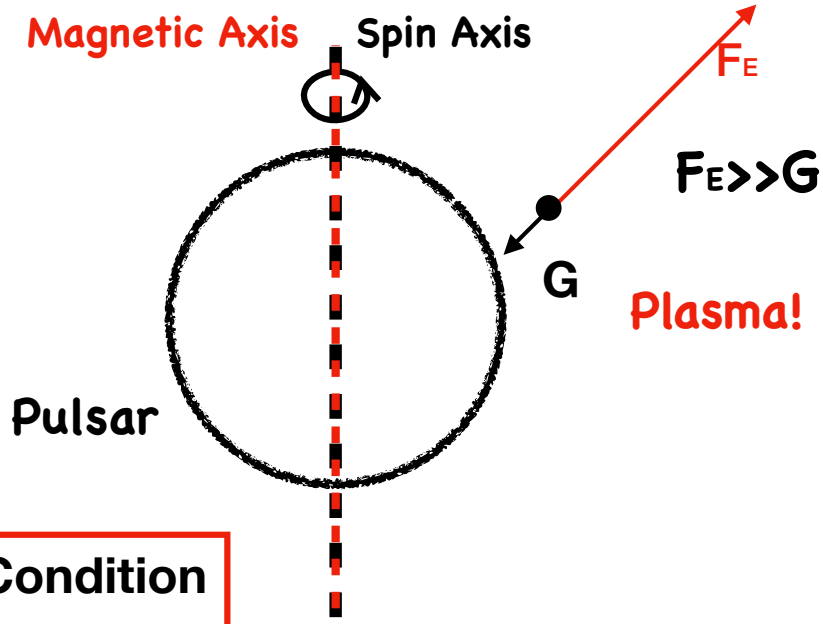
Electric & Magnetic Fields around Pulsar

- **Compare the EM force and the gravitational force**

  - for an electron:

$$8 \times 10^{11} B_{12} R_6^3 \cos^2\theta / PM$$

e.g. For the **crab nebula**, B_{12} is 4x10^12(gauss)/10^12, R_6 is about 10^6cm/10^6, for an **electron ~ 7x10^14**.



Conclusion:
Pulsar must be surrounded by plasma.

Force Free Condition

$$\rho\mathbf{E} + \frac{1}{c}\mathbf{j} \times \mathbf{B} = 0$$

$$E \cdot B = 0$$

Electric & Magnetic Fields around Pulsar

- **Near Zone and Wind Zone Field Lines**

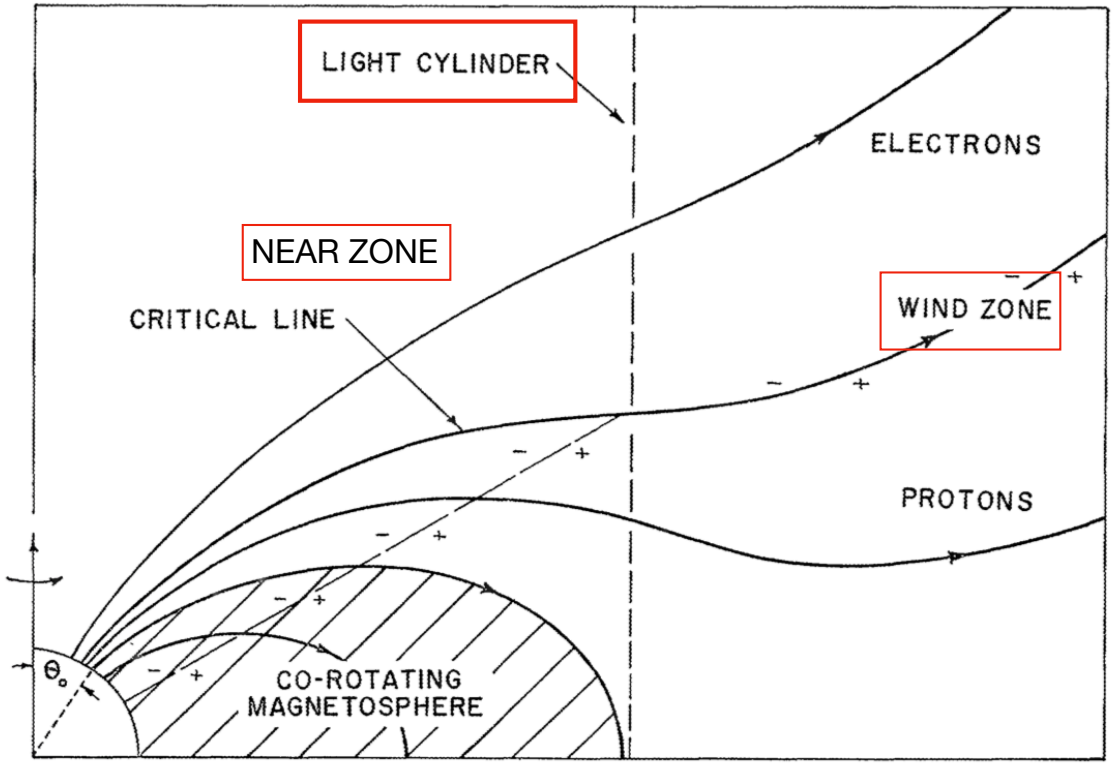


FIG. 1.—Schematic diagram showing the corotating magnetosphere and the wind zone. Star is at lower left.

Electric & Magnetic Fields around Pulsar

- **Motion Equations:** $m_e\dot{\boldsymbol{\beta}} = e(\boldsymbol{E} + \boldsymbol{\beta} \times \boldsymbol{B}) + m_e g$

omitted

$= 0$

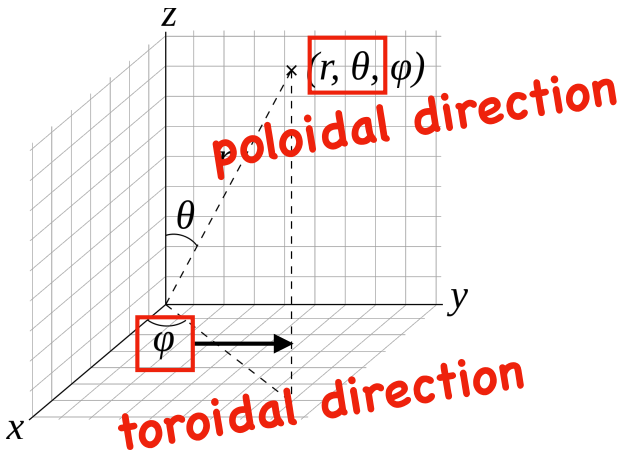
force free

Steady-state & Axial Symmetry + $\boldsymbol{E} \cdot \boldsymbol{B} = 0$ = **Electric Field** $\boldsymbol{E} + \frac{(\boldsymbol{\Omega} \times \boldsymbol{r})}{c} \times \boldsymbol{B} = 0$

Charged Particle Motion Condition

$$\beta_p = \kappa B_p \;\&\; \beta = v/c$$

+



Charged Particle Motion Solution

$$\beta = \kappa B + (\Omega r/c) \sin\theta\phi$$

Electric & Magnetic Fields around Pulsar

- **Charge & Current Density**

Electric Field

$$E = -\frac{\Omega r \sin\theta}{c}\phi \times B_p$$

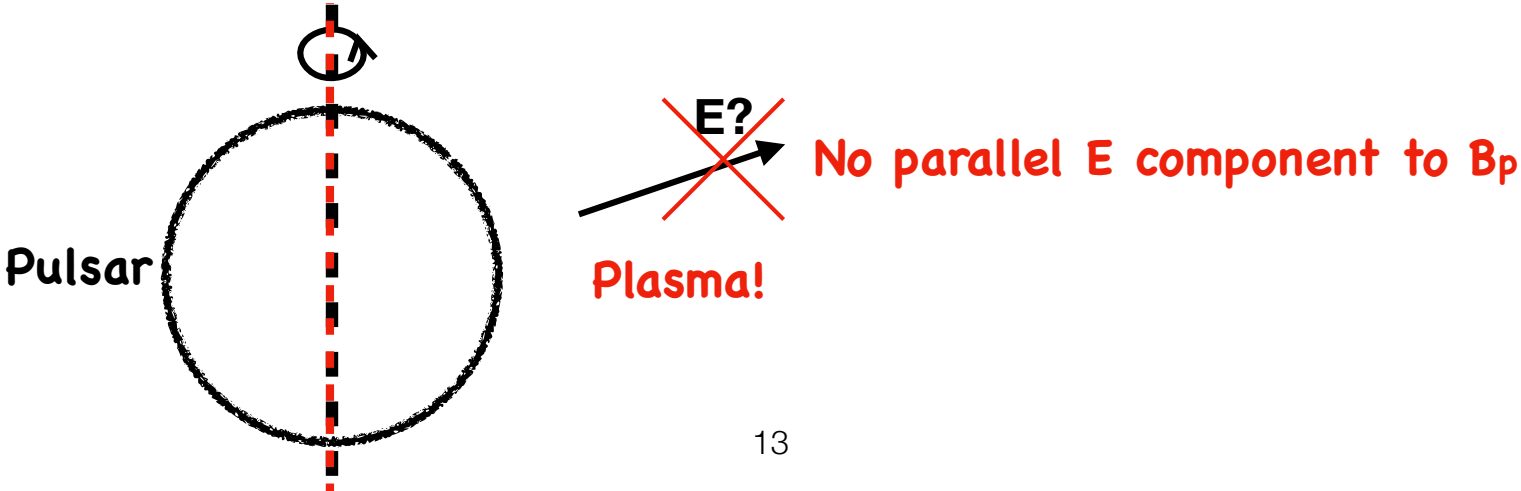
Goldreich-Julian Charge Density

$$\rho = \frac{\nabla \cdot E}{4\pi} = \frac{-\Omega \cdot B}{2\pi c}\frac{1}{[1 - (\Omega r/c)^2 \sin^2\theta]}$$

Charged Particle Number Density

$$n = 7 \times 10^{-2}\frac{B_z}{P}\ \text{particles cm}^{-3}$$

Minimum charge density to shield electric field



Electric & Magnetic Fields around Pulsar

- **near zone**

Magnetic Fields

$$B_t = -(\Omega r/c\beta_p)\ \sin\theta B_p$$
$$B_p = r^{-2}\Psi(\theta)$$

Electric Fields

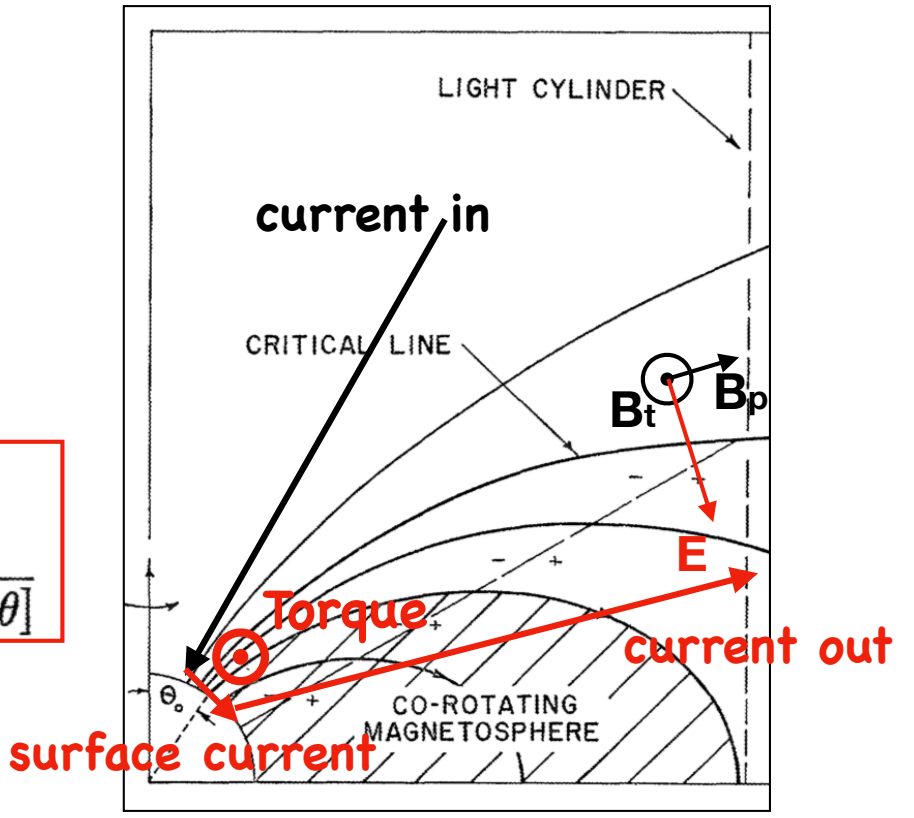
$$E = -\frac{\Omega r\ \sin\theta}{c}\phi \times B_p$$

Goldreich-Julian Charge Density

$$\rho = \frac{\nabla\cdot E}{4\pi} = \frac{-\Omega\cdot B}{2\pi c}\frac{1}{[1-(\Omega r/c)^2\ \sin^2\theta]}$$

Goldreich-Julian Current Density

$$J_t = (\Omega r/c)\ \sin\theta\rho$$



Light Cylinder

Electric & Magnetic Fields around Pulsar

- **wind zone**

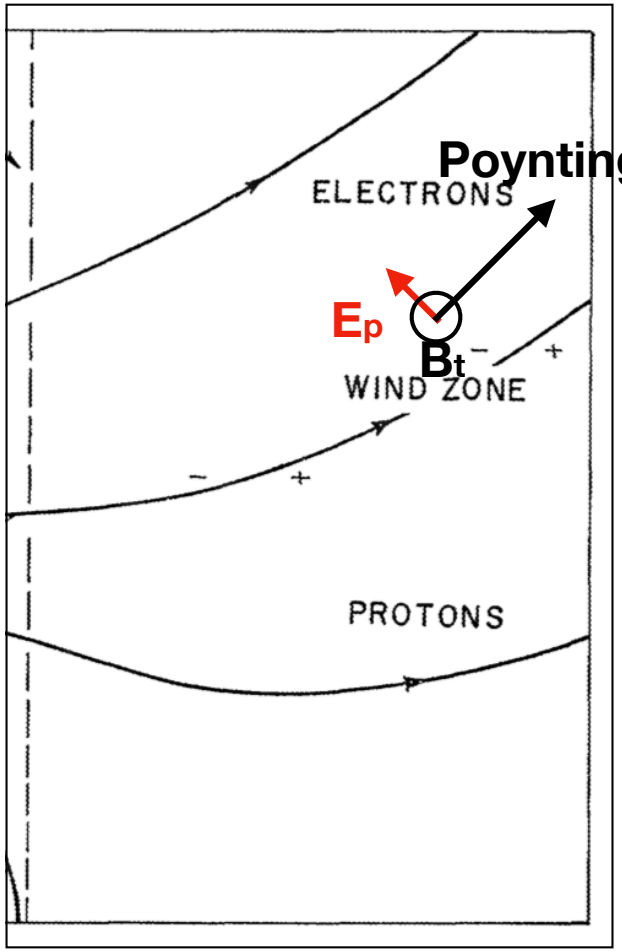
EM Fields

$$B_t = E_\theta = -\tfrac{1}{2}\left(\frac{\Omega R}{c}\right)^2\left(\frac{R}{r}\right)B_0 \sin\theta \frac{\Psi(\theta)}{I_1}$$

$$B_p = \tfrac{1}{2}\left(\frac{\Omega R}{c}\right)\left(\frac{R}{r}\right)^2 B_0 \frac{\Psi(\theta)}{I_1}$$

B_t is dominant in this zone

Note: I1 is the surface current flowing from north pole to equator



Poynting Vector:

$$\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{B} = |\boldsymbol{B_t}|^2 = \frac{1}{4}(\frac{\Omega r}{c})^4(\frac{R}{r})^2 B_0^2 \sin^2(\theta)(\frac{\Phi(\theta)}{I_1})^2 \propto \frac{1}{r^2}$$

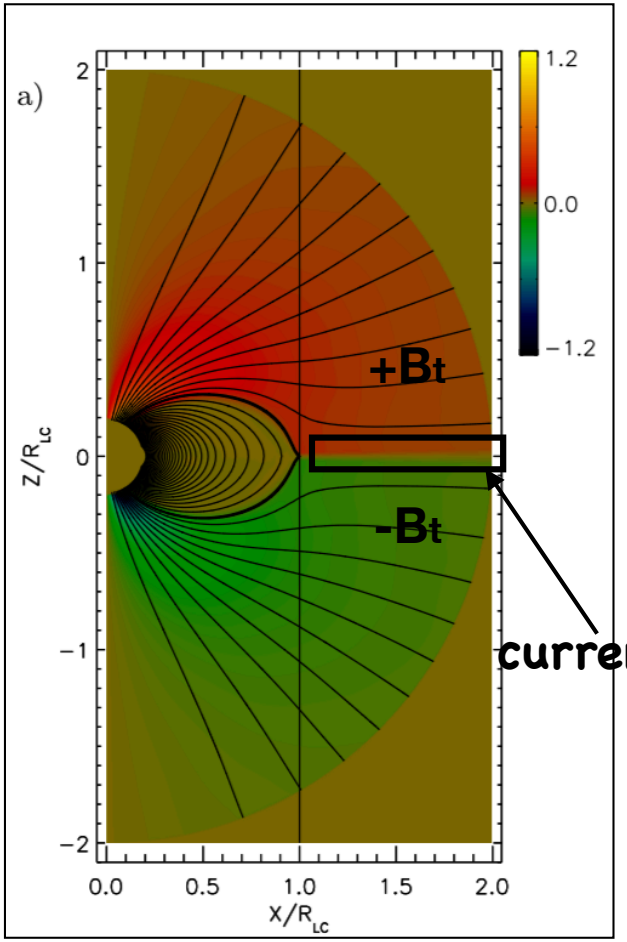
Poynting Flux:

$$L = (1 \pm 0.1)\mu^2\Omega^4/c^3$$

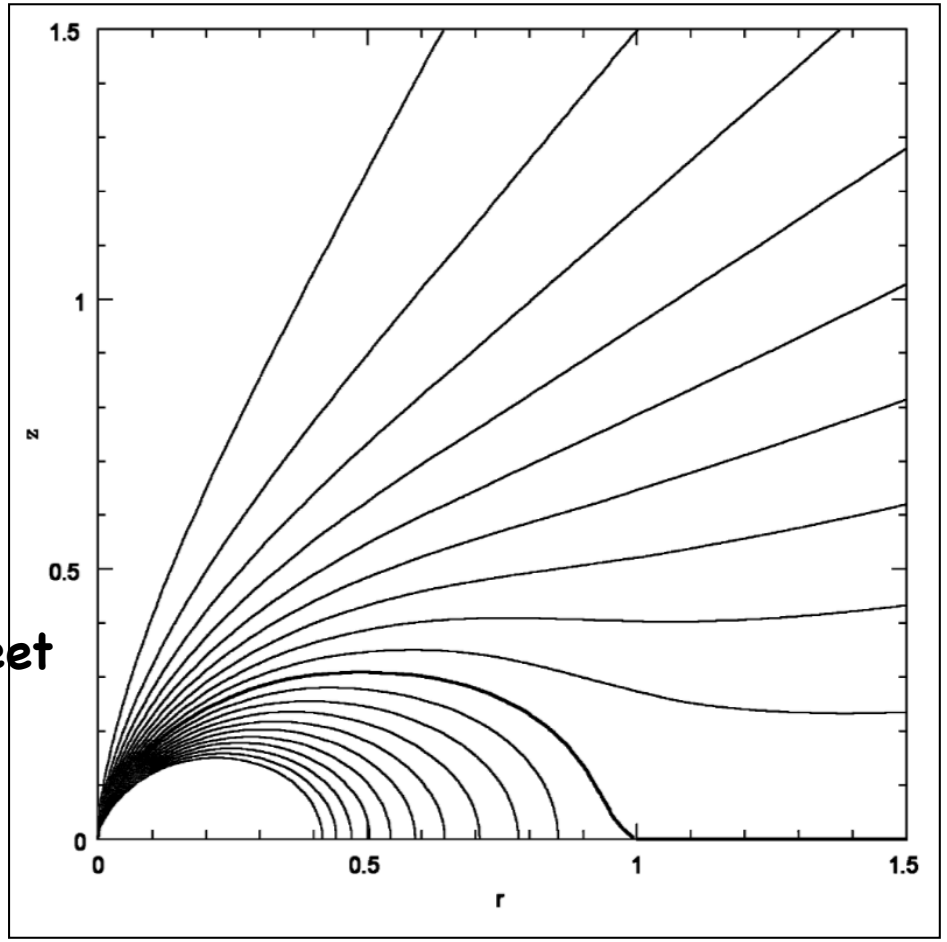
Light Cylinder

Electric & Magnetic Fields around Pulsar

- **near zone and wind zone field lines(force free condition)**



(Anatoly Spitkovsky, 2006)

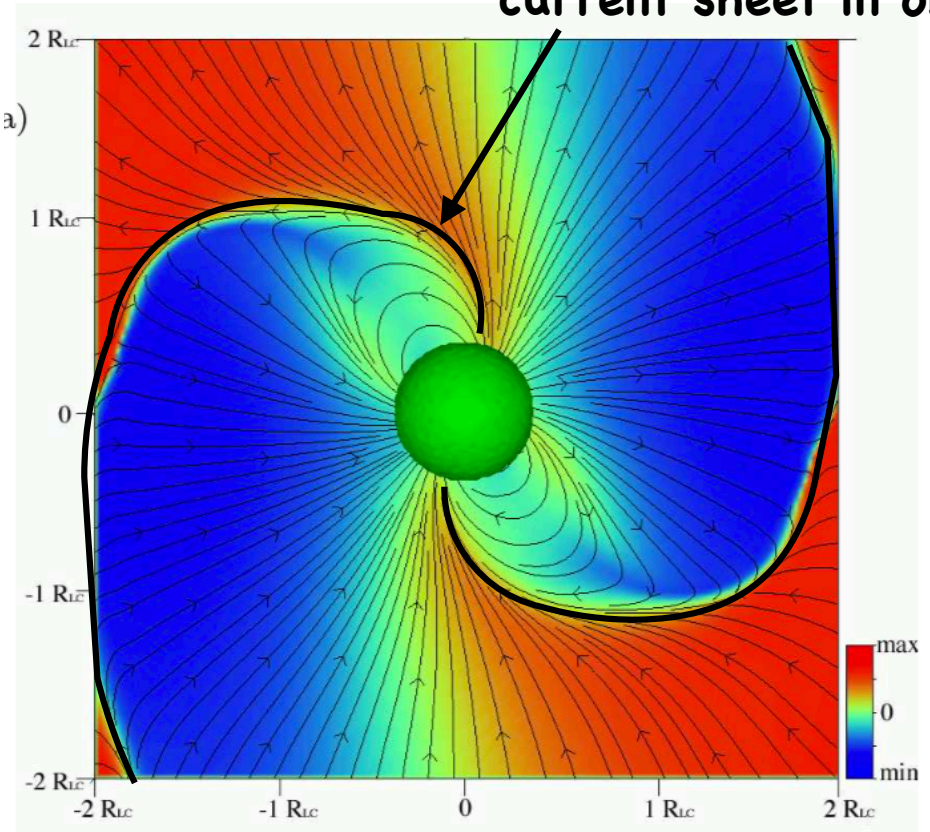


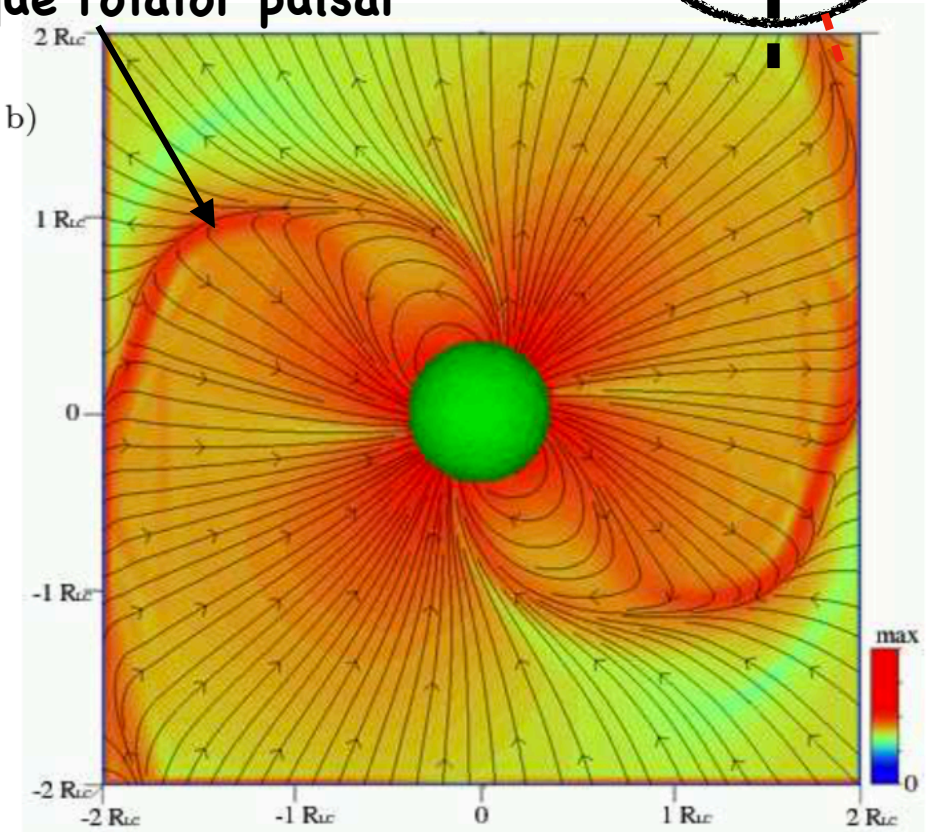
(Andrei Gruzinov, 2005)

Inclined Axis Properties

- **Pulsar with Inclined Axis(force free condition)**

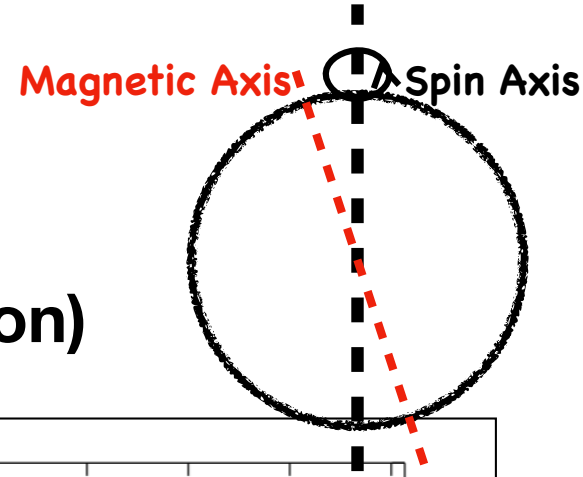
current sheet in oblique rotator pulsar



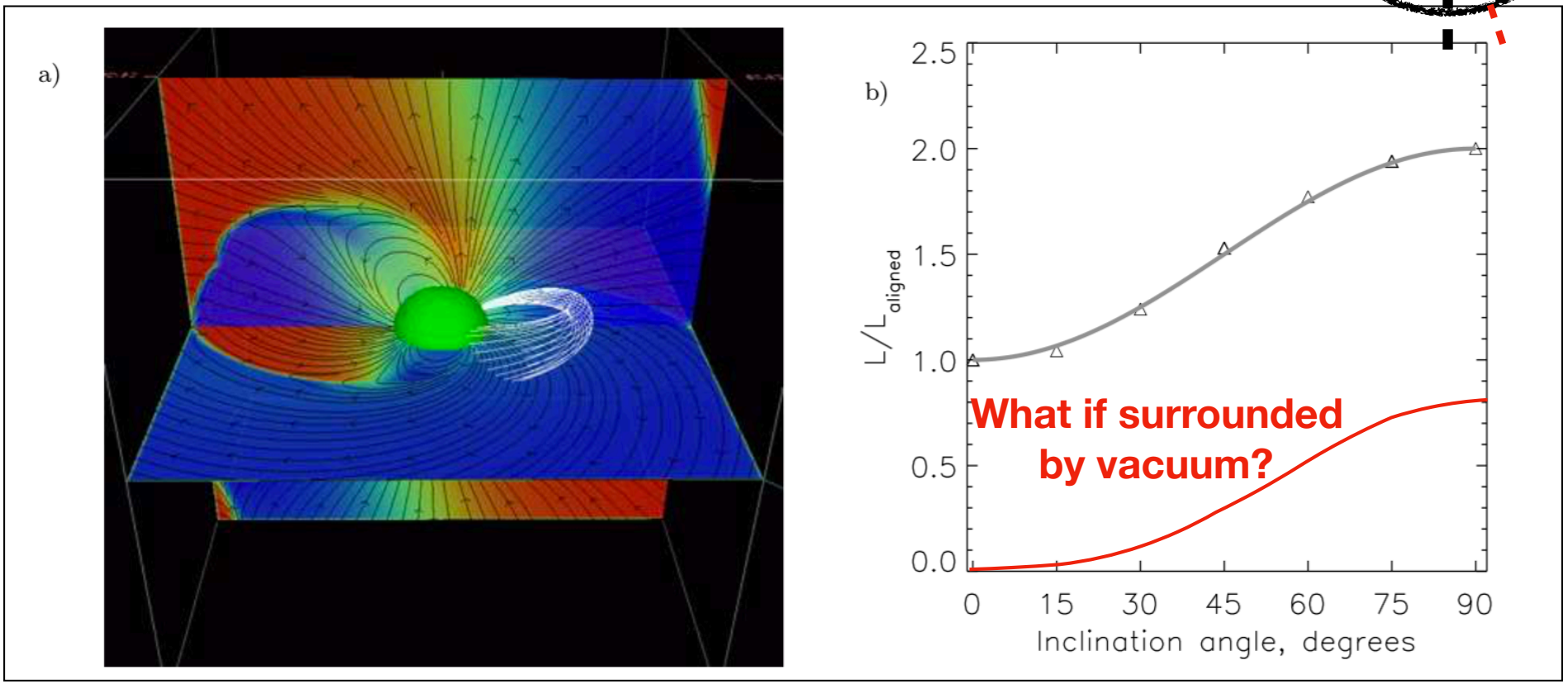


(Anatoly Spitkovsky, 2006)

Inclined Axis Properties



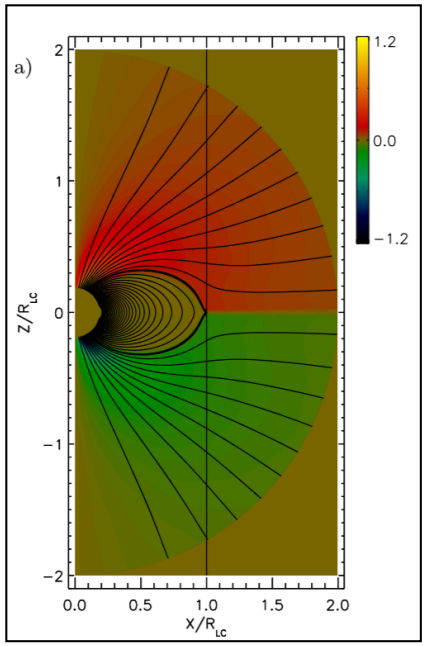
- **Pulsar with Inclined Axis(force free condition)**

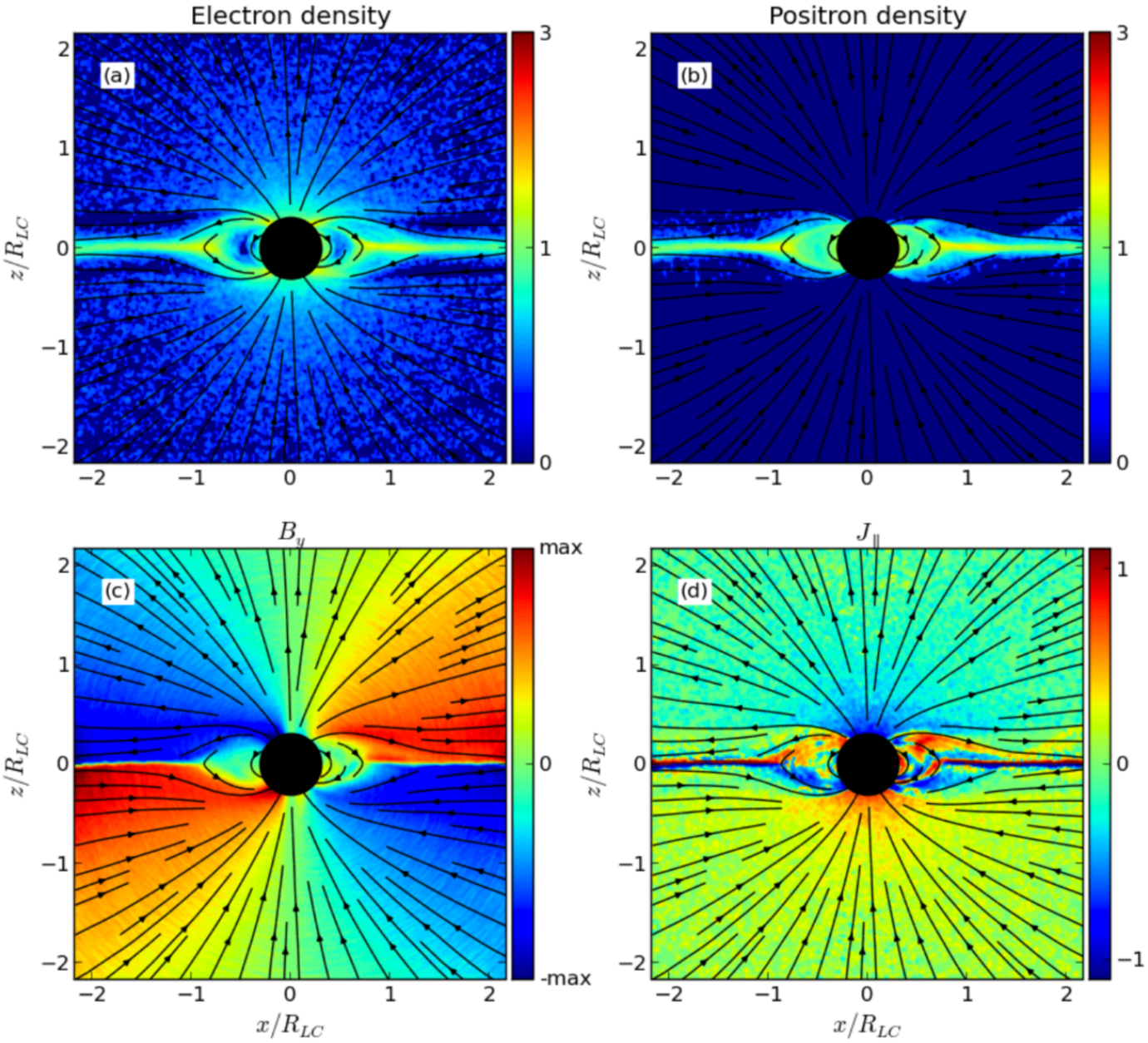


(Anatoly Spitkovsky, 2006)

Numerical Simulations of Pulsar

particle-in-cell simulation with aligned axes (first principle)

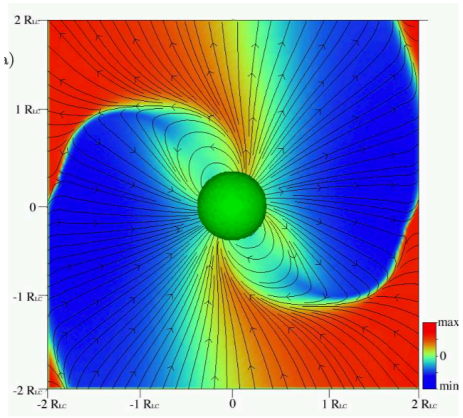


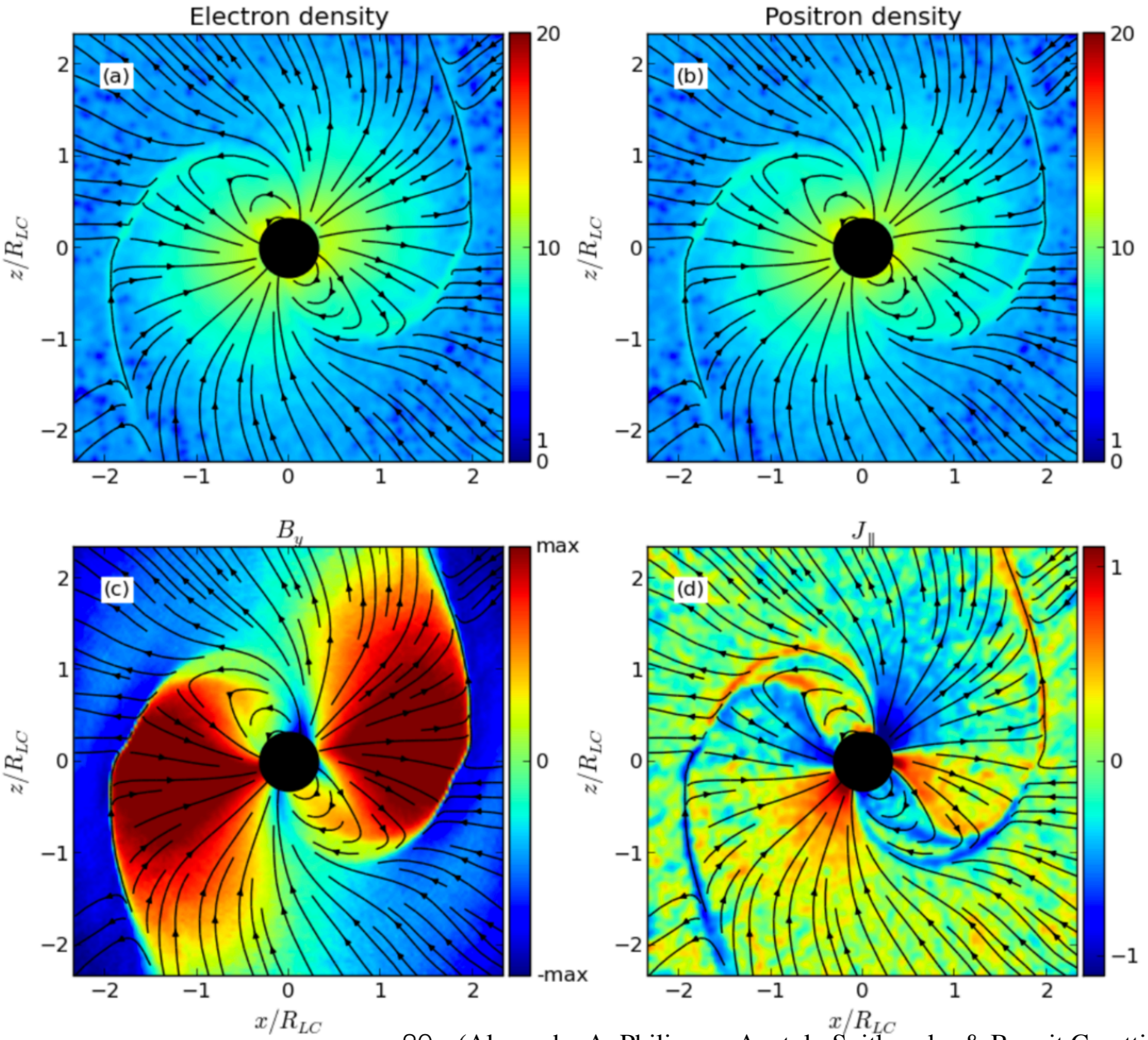


 (Alexander A. Philippov, Anatoly Spitkovsky & Benoit Cerutti, 2014)

Numerical Simulations of Pulsar

particle-in-cell simulation with inclined axes (first principle)





 (Alexander A. Philippov, Anatoly Spitkovsky & Benoit Cerutti, 2014)

Summary

Electro-Magnetic field properties of pulsar

Magnetic dipole field & dipole radiation with aligned axes

Mechanism of pulsar spin down & radiation

Force free & particle in cell simulation of pulsar EM fields