Title: Approaches to modeling pulsar magnetospheres

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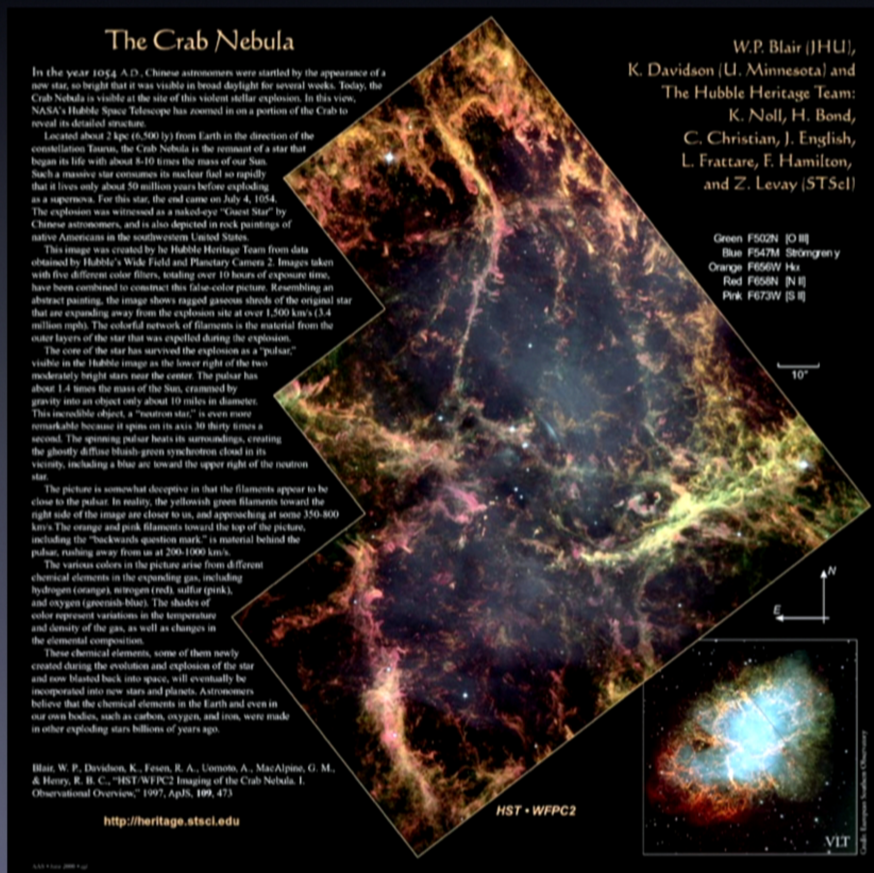
Abstract: Pulsars are rotating magnetized neutron stars that emit
broadband pulses of radiation. Our ability to model magnetospheres of pulsars has been hampered by the difficulty of solving the self-consistent behavior of strongly magnetized relativistic plasmas. I will describe
recent progress in numerical modeling of magnetically-dominated plasmas and show applications to pulsar magnetospheres in increasing levels of realism, including ideal and resistive force-free,
relativistic MHD and kinetic models. The knowledge of the magnetospheric shape together with the new observations of gamma-ray emission from pulsars with Fermi telescope allow to directly constrain the location and physics of the acceleration regions in the magnetosphere and the origin of high energy emission. The pulsar magnetosphere is a prototype for other strongly magnetized
astrophysical objects, and I will discuss how the lessons from pulsar modeling can be useful in predicting EM counterparts to gravitational wave sources.

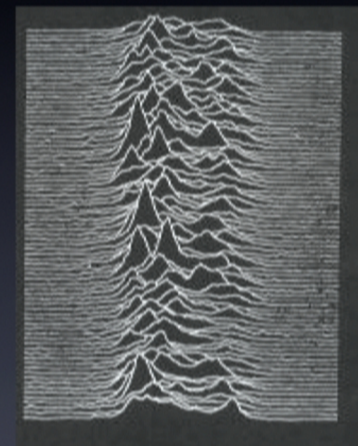
Approaches to modeling pulsar magnetospheres

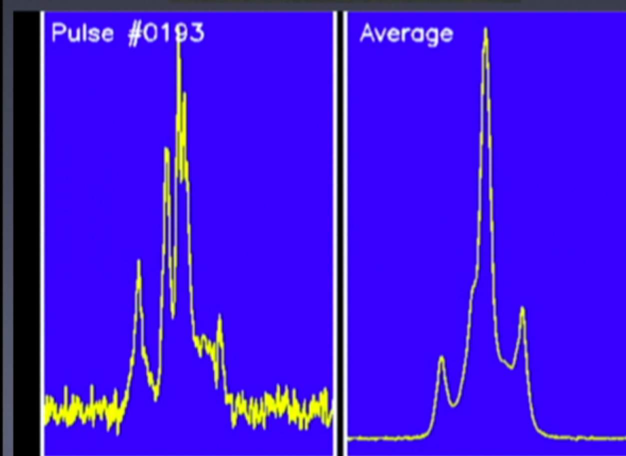
Anatoly Spitkovsky (Princeton)

(with J. Arons, X. Bai, J. Li, L. Sironi, A. Tchekhovskoy)

Pulsars are rotating neutron stars, born in supernova explosions. They emit periodic pulses of radiation and slow down with time.

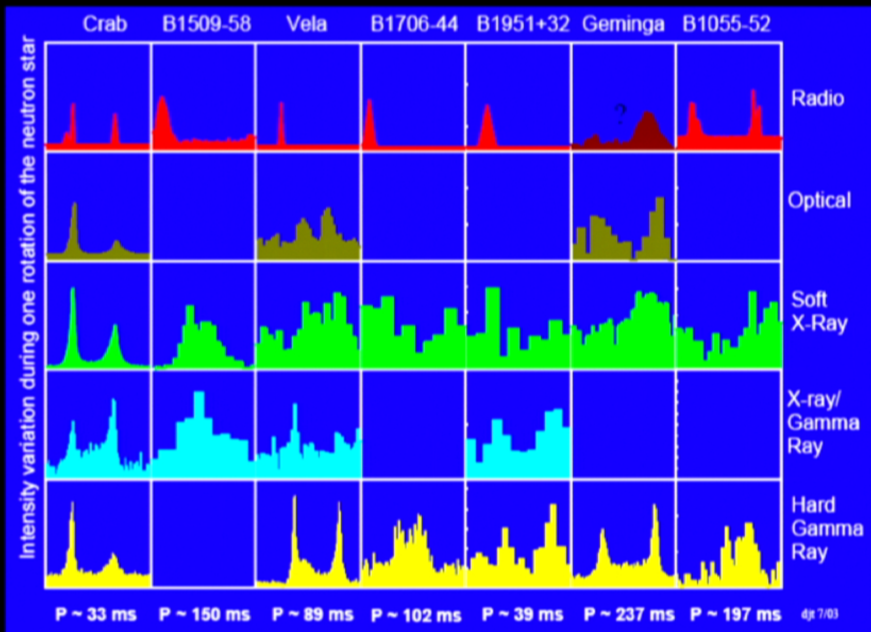


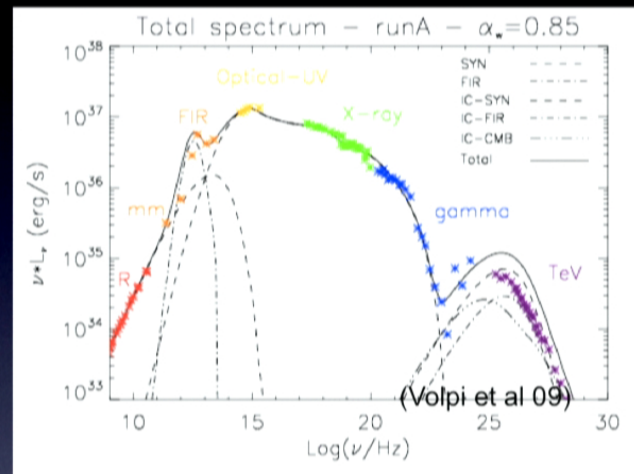


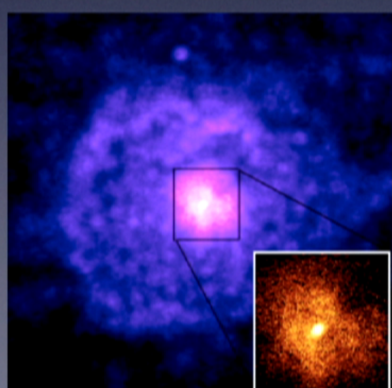


•Broadband pulsed emission, now > 100 GeV (Veritas).

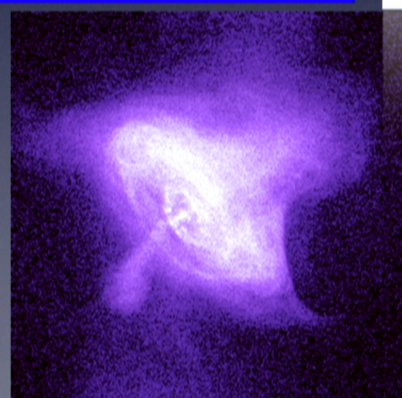
•PWNe: radio-TeV. 10^{40} pairs/ sec. Also, flares!



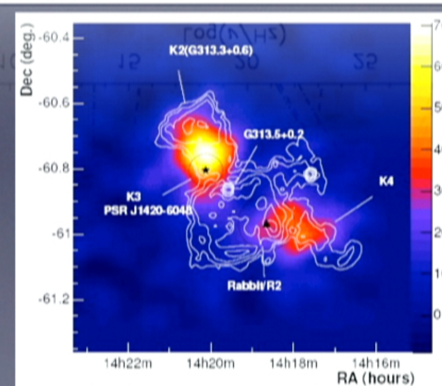




G21.9 (Safi-Harb et al 2004)



Crab (Weisskopf et al 2000)



HESS J1420 (Aharonian et al 2006)

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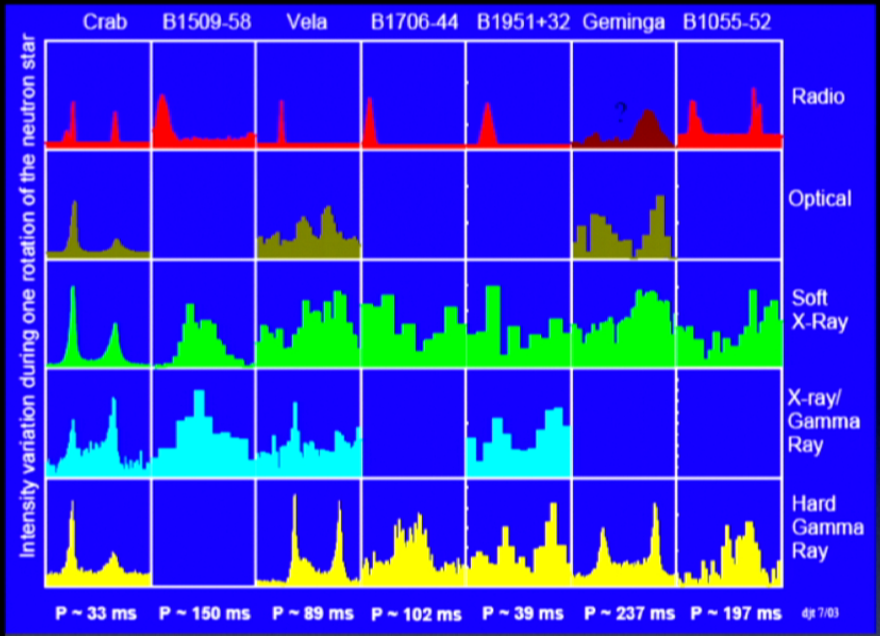

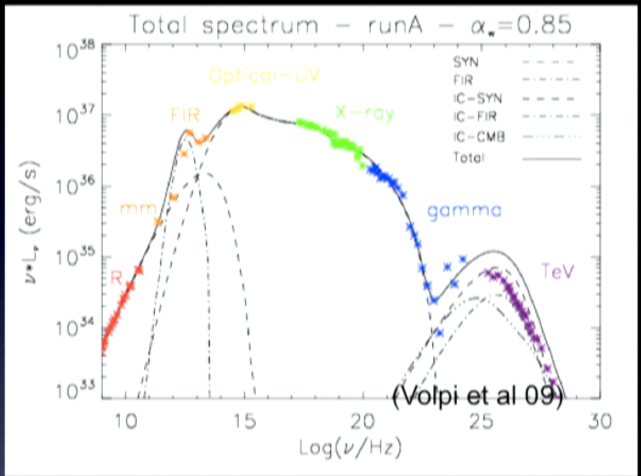

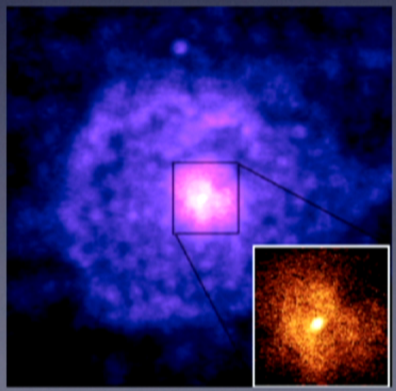
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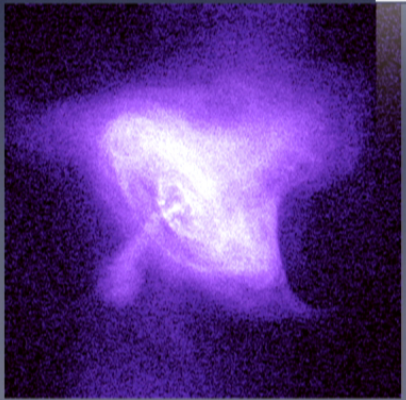
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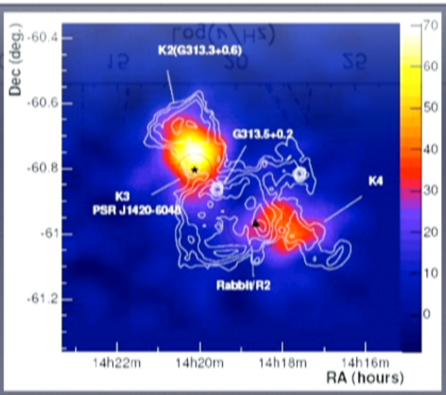

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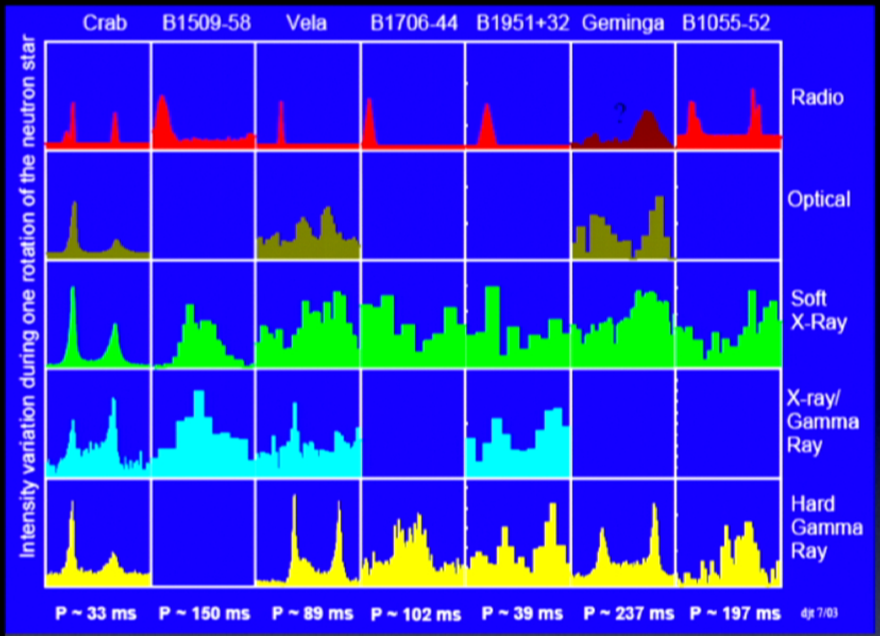

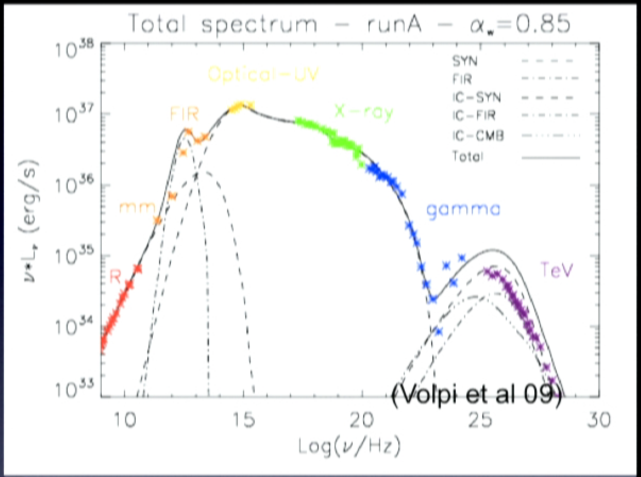

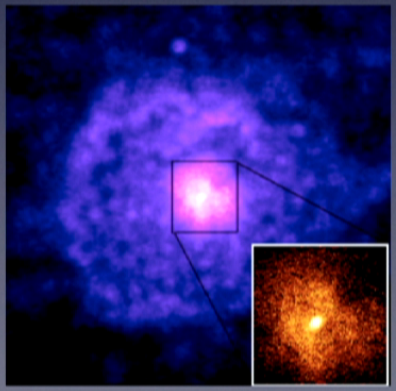

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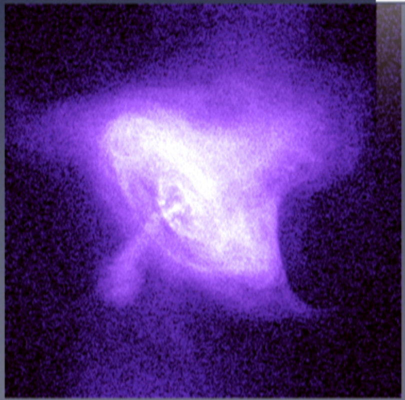

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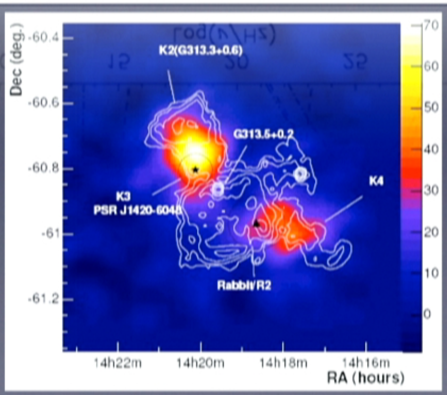

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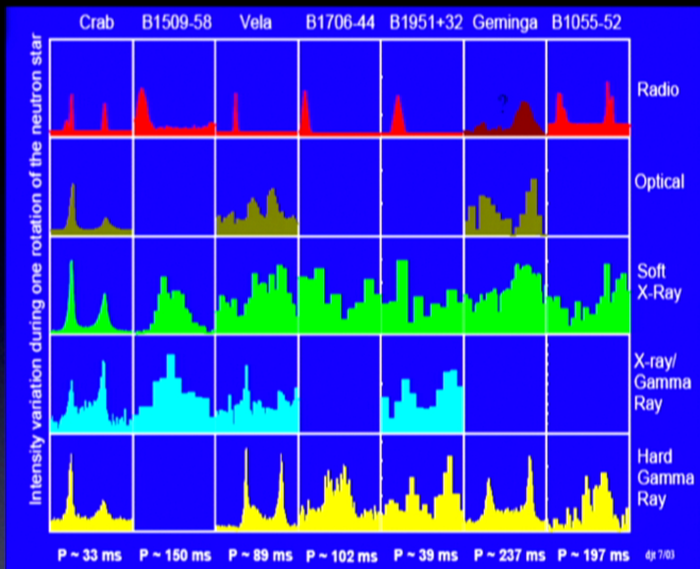
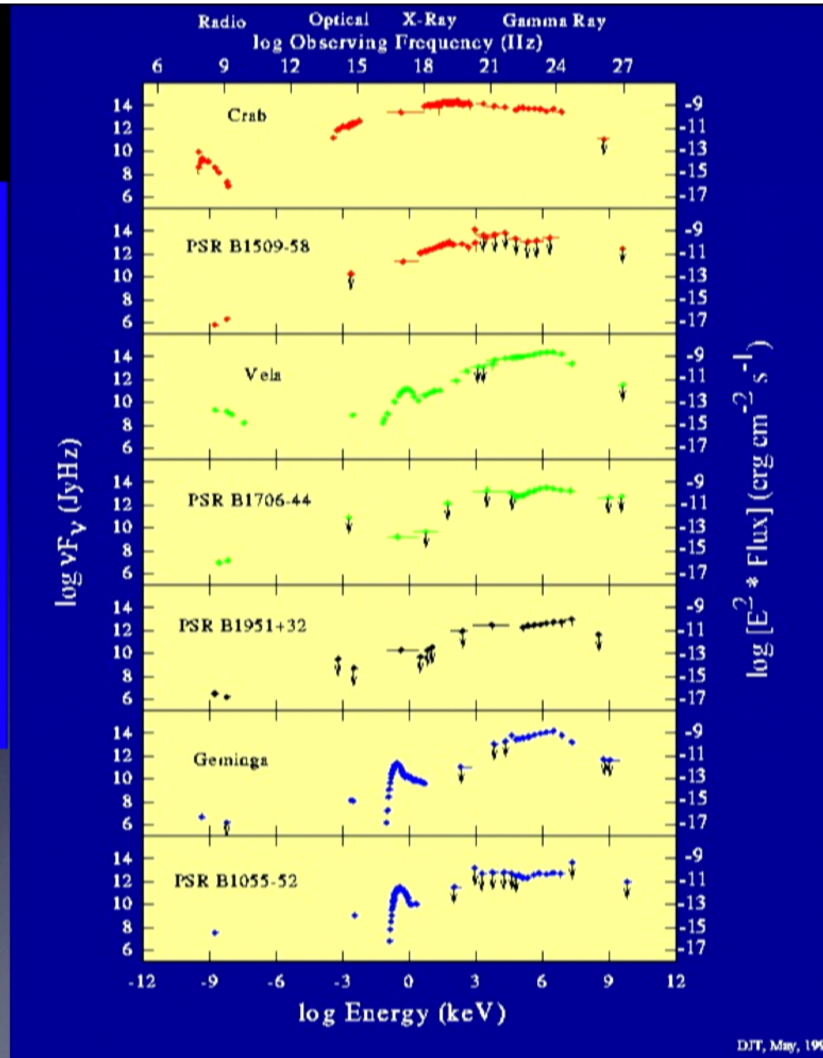


Crab
B1509-58
Vela
B1706-44
B1951+32
Geminga
B1055-52
Intensity variation during one rotation of the neutron star
Radio
Optical
Soft X-Ray
X-ray/ Gamma Ray
Hard Gamma Ray
P ~ 33 ms
P ~ 150 ms
P ~ 89 ms
P ~ 102 ms
P ~ 39 ms
P ~ 237 ms
P ~ 197 ms



Radio
Optical
X-Ray
Gamma Ray
log Observing Frequency (Hz)
Crab
PSR B1509-58
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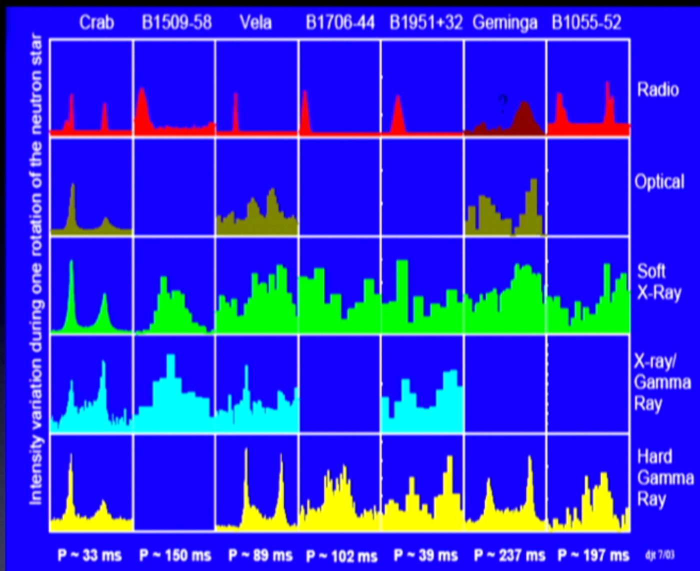
log [E^2 * Flux] (erg cm^{-2} s^{-1})
log Energy (keV)
DJT, May, 1998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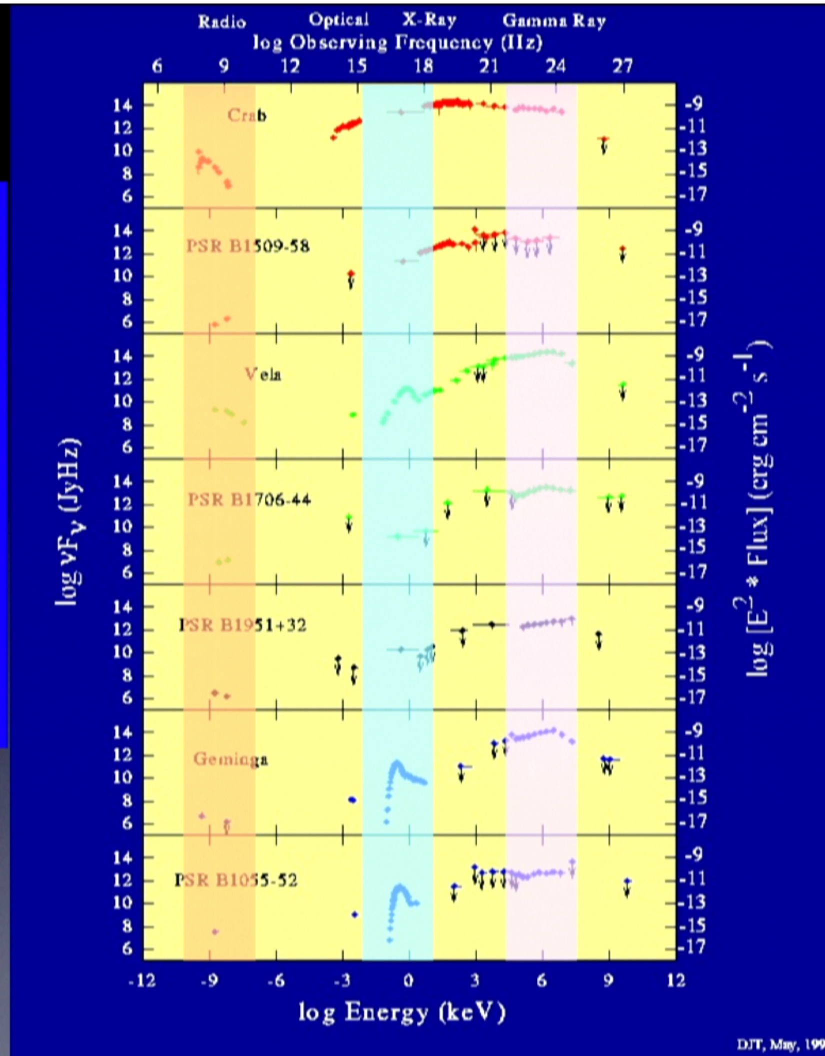
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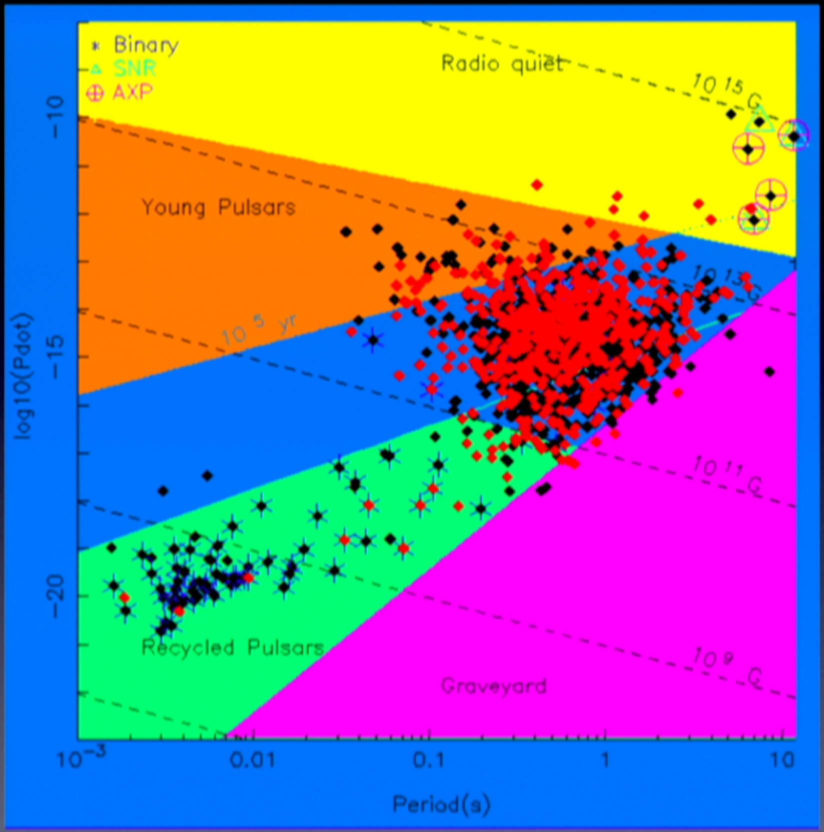
Main energy loss is invisible, but detectable -- pulsar spin-down

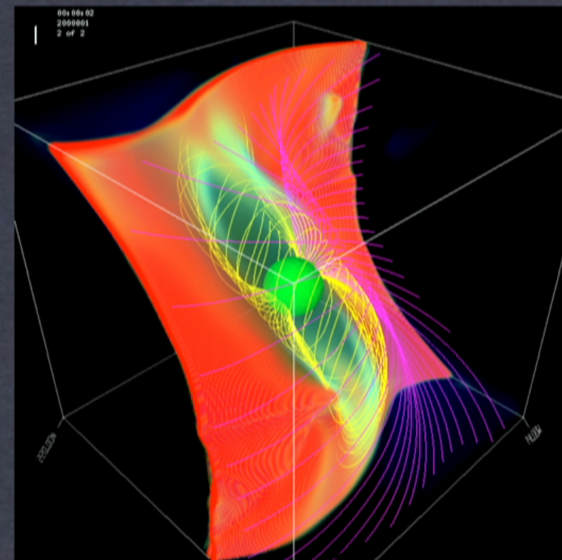
Leaves as magnetized wind (carrying Pointing flux)

The fact that γ-ray power reaches 10-s of percent of spin-down power implies that we are tapping the main magnetospheric currents

Need to understand how magnetosphere works

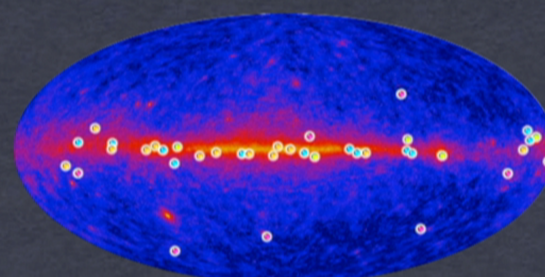


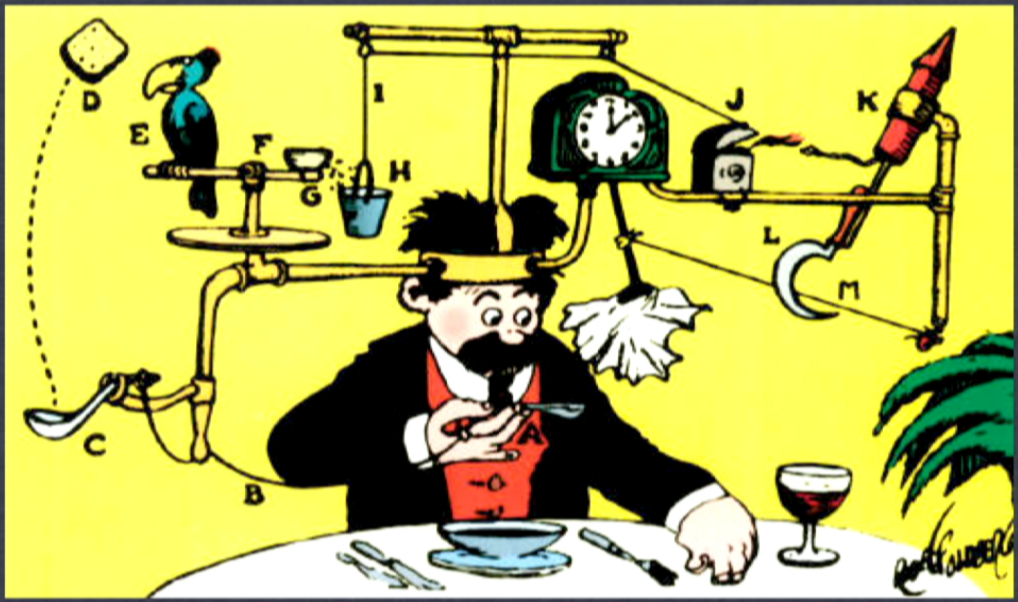
Pulsars in Fermi era



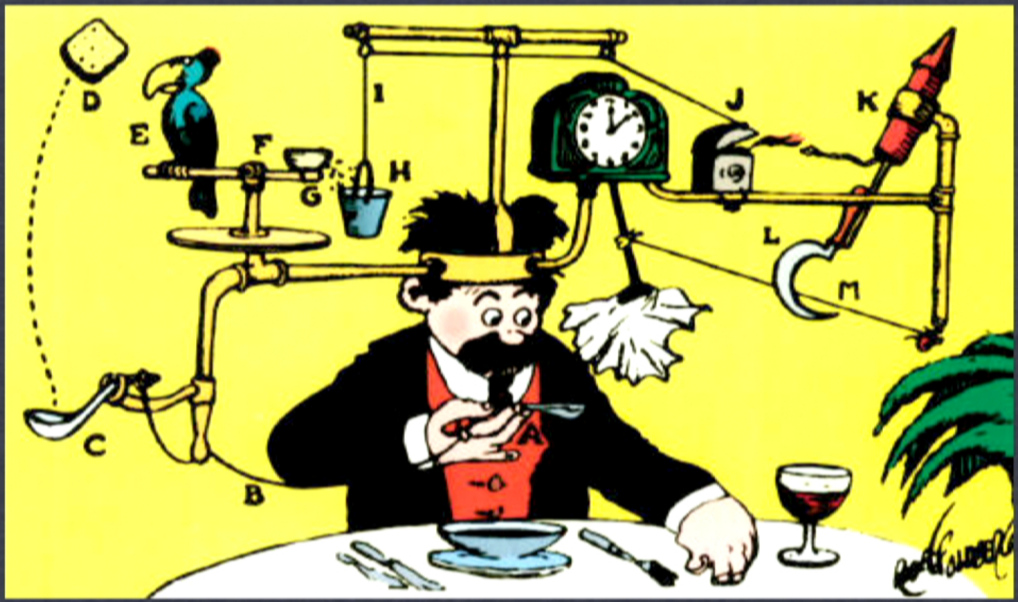
Why pulsars are interesting?

- Unique laboratory for strong B fields and relativistic plasmas
- Prototypes of other astrophysical objects: accretion disks, jets, black hole magnetospheres
- Incredible electromagnetic machines
- Not understood for > 40 yrs
- Prime sources for Fermi





self-operating napkin



self-operating napkin

Pulsars: observationally driven

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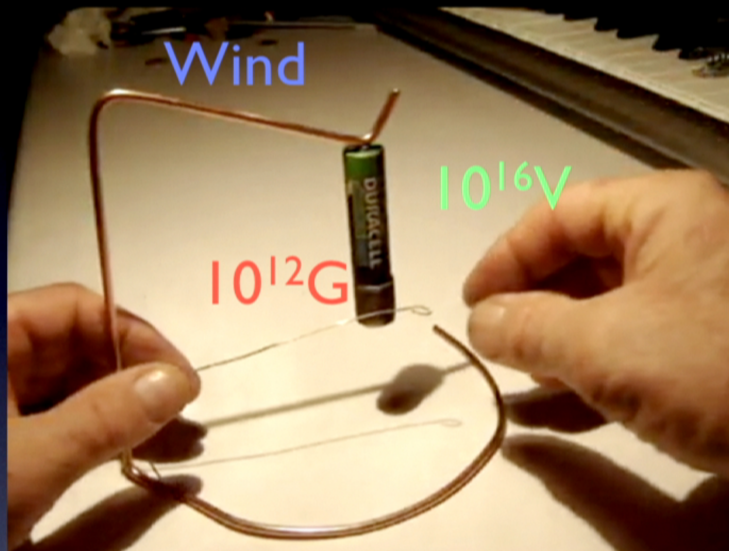
Pulsar theory:

Open questions:

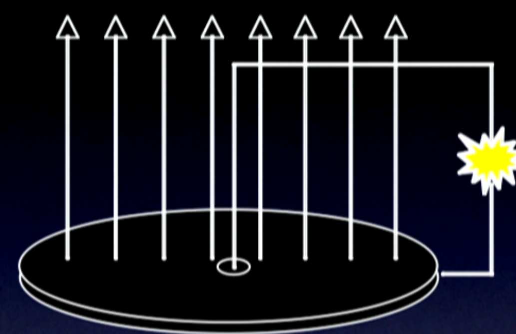
- The structure of the magnetosphere is the primary question, as all emission physics must be done in the context of proper magnetospheric geometry.

- Related question is the nature of the spin-down: most energetic, but mostly invisible, process in normal pulsars.

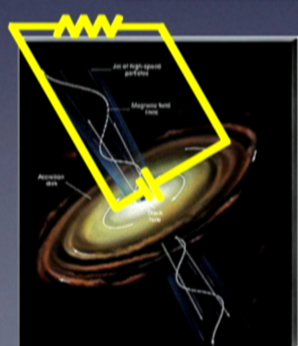
Pulsar physics in space



$$\phi_0 = \Omega B a^2 / c$$



Faraday disk
Unipolar induction



from R. Blandford

Rule of thumb: $V \sim \Omega\Phi$; $P \sim V^2 / Z_0 = I\,V$

Crab Pulsar

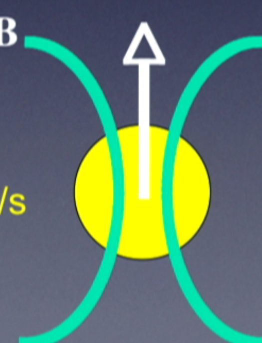
- $B \sim 10^{12}$ G, $\Omega \sim 200$ rad s^{-1}, $R \sim 10$ km
- Voltage $\sim 3 \times 10^{16}$ V; $I \sim 3 \times 10^{14}$ A; $P \sim 10^{38}$ erg/s

Magnetar

- $B \sim 10^{14}$ G; $P \sim 10^{44}$ erg/s

Massive Black Hole in AGN

- $B \sim 10^{4}$ G; $P \sim 10^{46}$ erg/s



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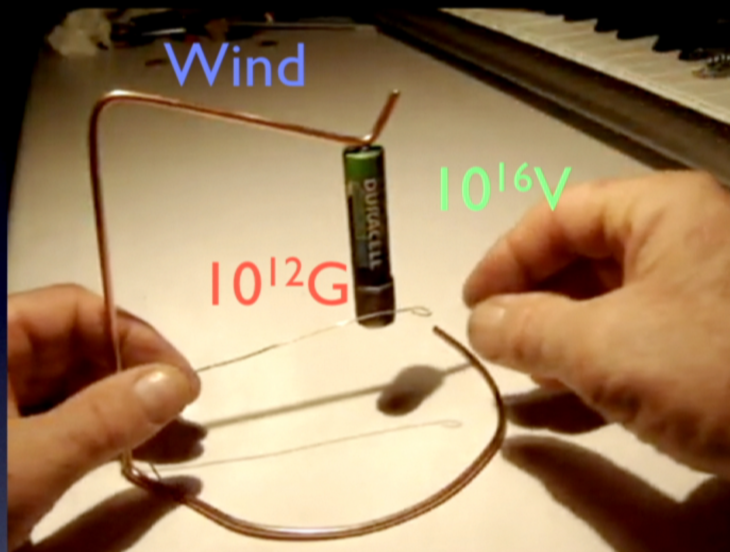

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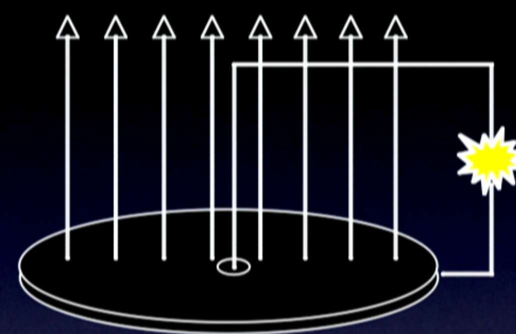

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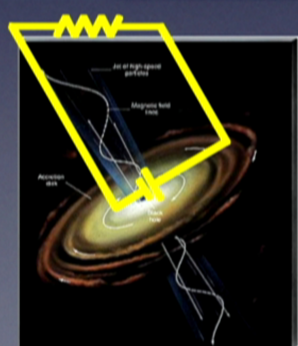

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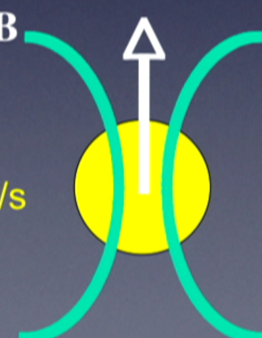
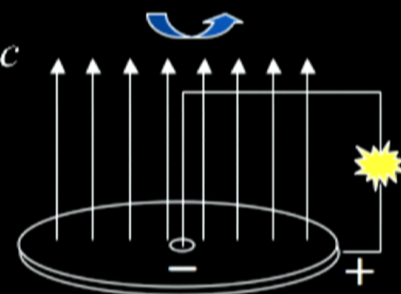


Plasma source

Where does the plasma come from?

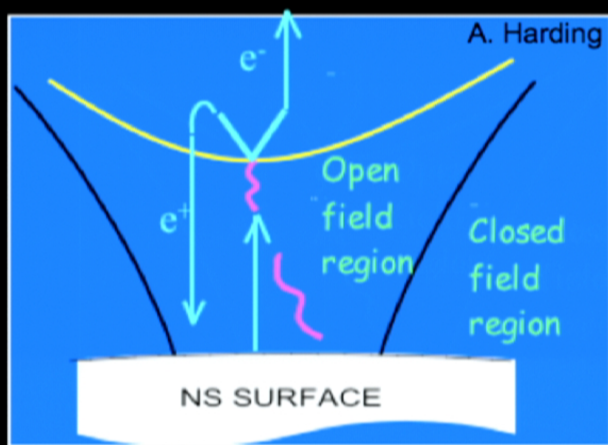
$\phi_0 = \Omega B a^2 / c$



Faraday disk: unipolar induction

Polar cap is a space-charge limited accelerator.
Accelerated primary particles radiate curvature radiation, and pair produce in the strong field.
Pair cascade shorts out E*B.

$\gamma_{\text{primary}} \sim 10^7 \quad \gamma_{\text{secondary}} \sim 10^{2-3} \quad \sigma_{\text{LC}} \sim 10^4$



Arons & Scharleman 79, Muslimov & Harding 03

$$\vec{E} = -\frac{\vec{v}}{c} \times \vec{B} = -\frac{\vec{\Omega}}{c} \times \vec{R} \times \vec{B}$$

$$\frac{1}{4\pi} \nabla \cdot \vec{E} = \rho_{GJ} = -\frac{\vec{\Omega} \cdot \vec{B}}{2\pi c}$$

$$j_{GJ} = \rho_{GJ} c = -\frac{\vec{\Omega} \cdot \vec{B}}{2\pi}$$

Electrostatic accelerator, non-MHD region

After pair formation front -- enough plasma to use MHD.

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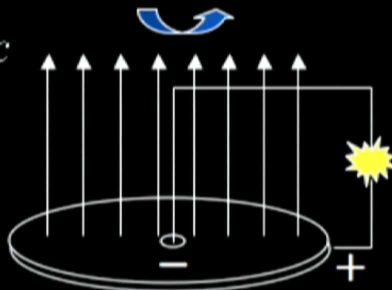

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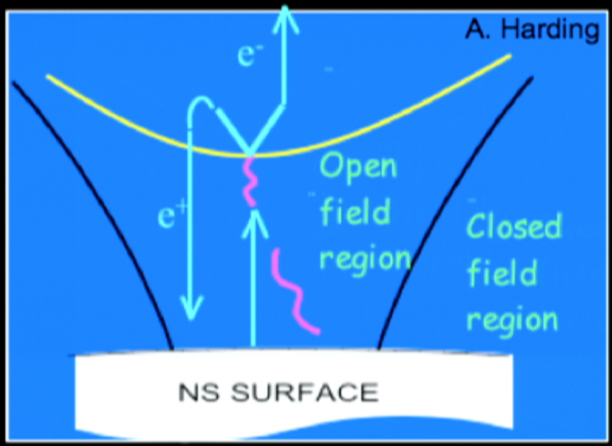

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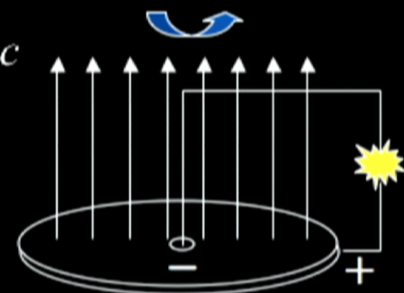

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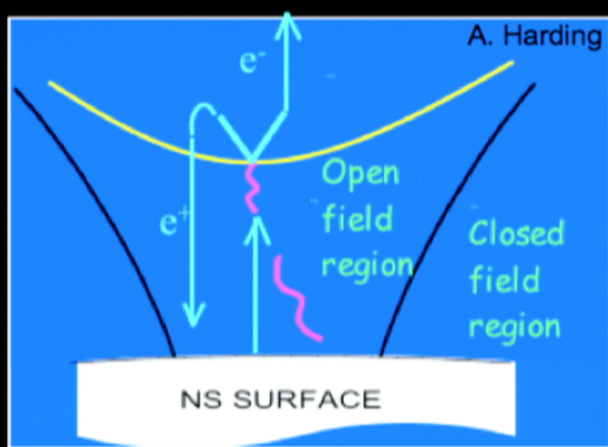

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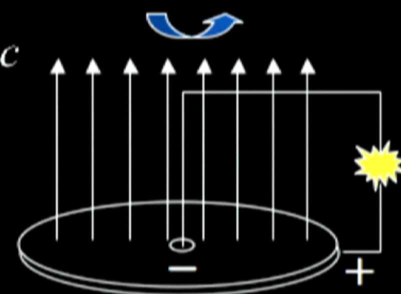

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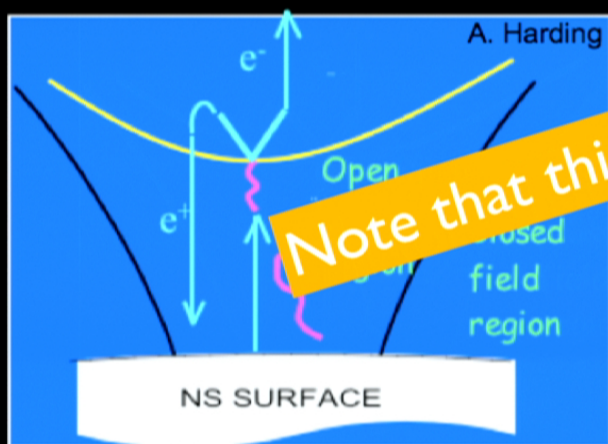

Note that this is a local model!

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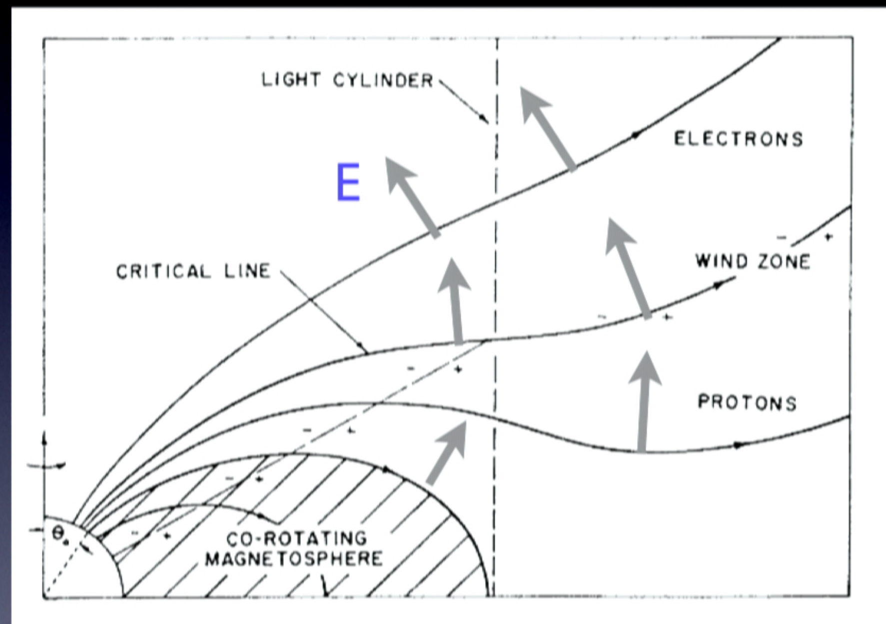
Pulsars: energy loss

$$\rho_{GJ} = -\frac{\vec{\Omega} \cdot \vec{B}}{2\pi c}$$

- Corotation electric field
- Sweepback of B field due to poloidal current
- ExB -> Poynting flux

- Electromagnetic energy loss



Goldreich & Julian 1969

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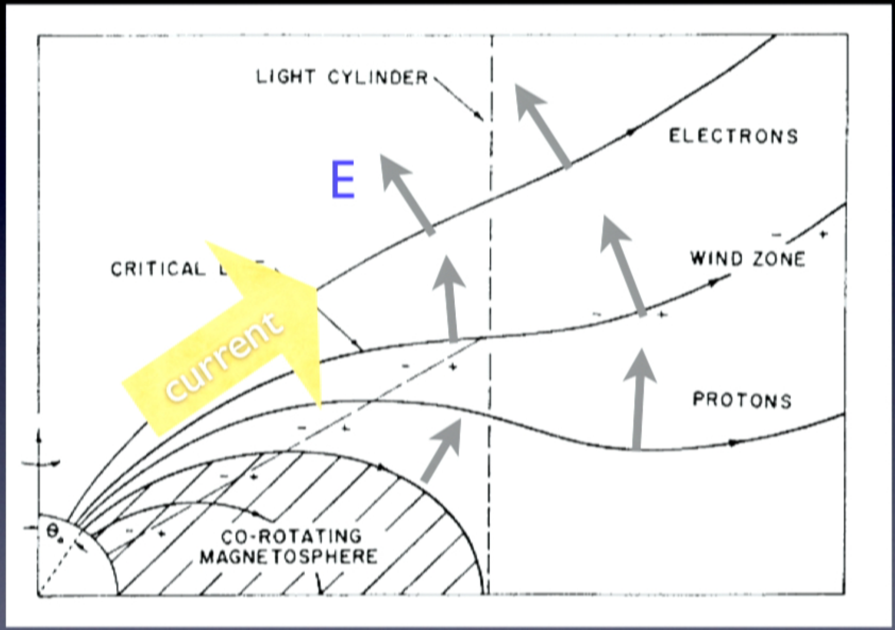

Goldreich & Julian 1969

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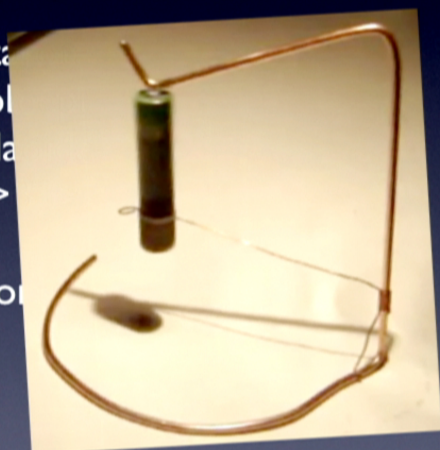
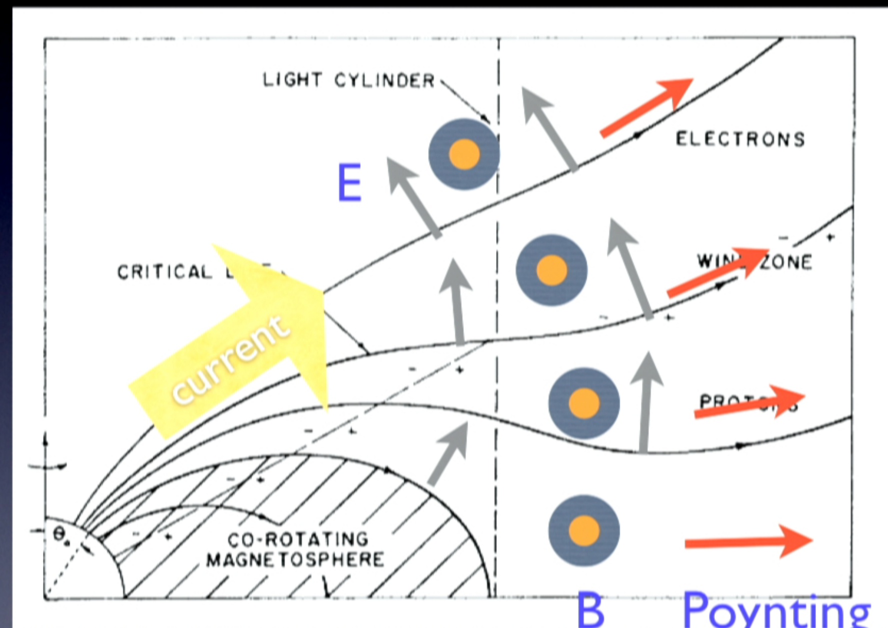




Goldreich & Julian 1969

Magnetospheric cartoon

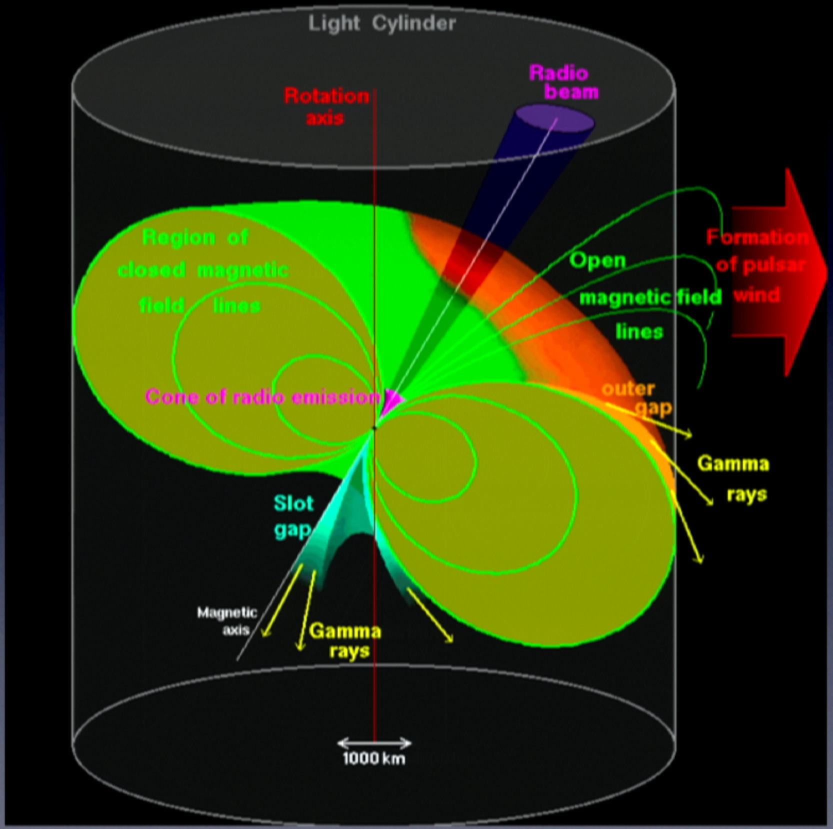
Open + closed (corotating) zones

Light Cylinder

Sweepback (part due to dB/dt, part due to current)

Current modifies the field

Can we model this?

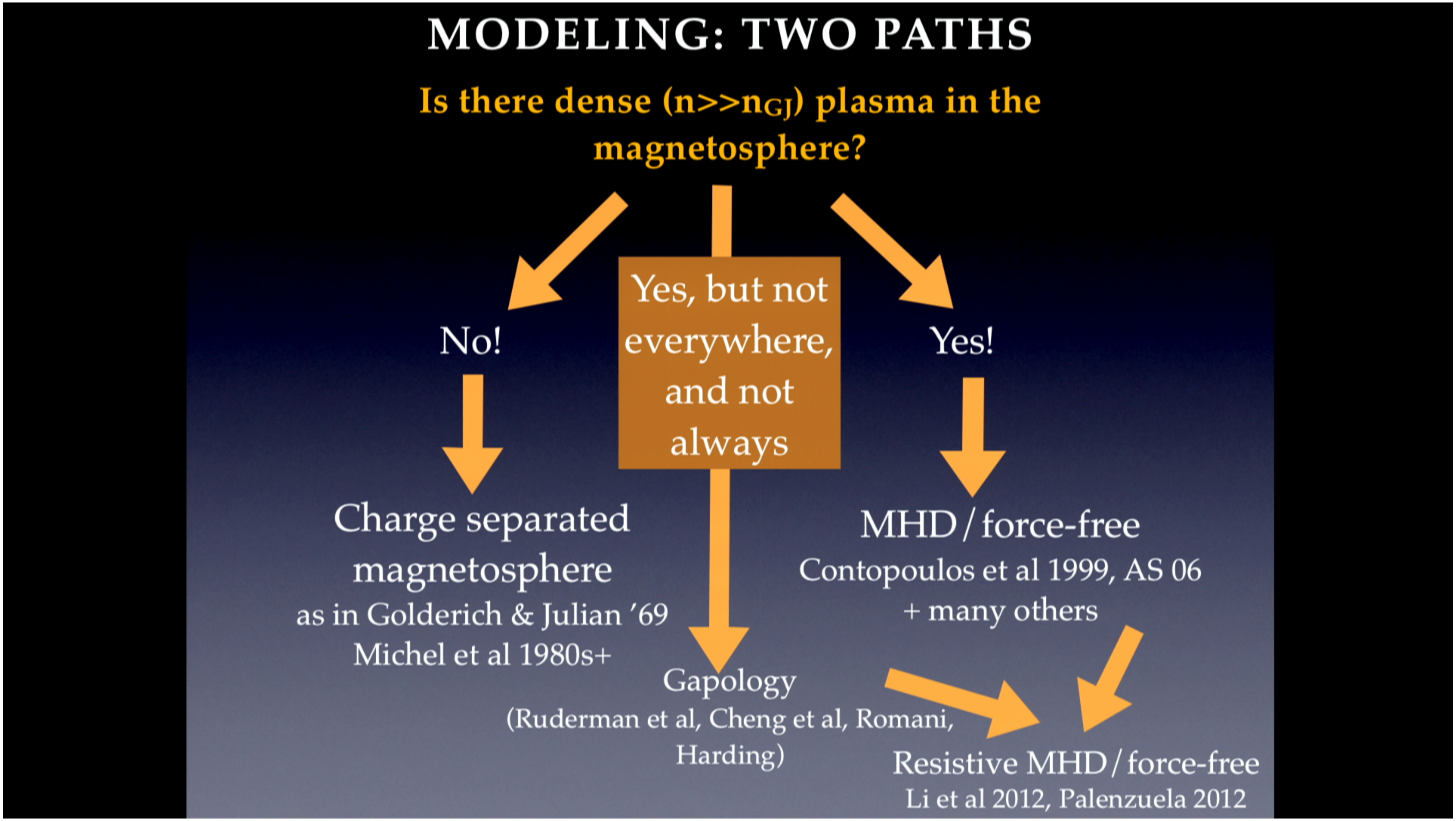


MODELING: TWO PATHS

Is there dense ($n \gg n_{GJ}$) plasma in the magnetosphere?

No!

Yes!


MODELING: TWO PATHS
Is there dense ($n >> n_{GJ}$) plasma in the magnetosphere?
No!
Yes, but not everywhere, and not always
Yes!
Charge separated magnetosphere
as in Golderich & Julian '69
Michel et al 1980s+
MHD / force-free
Contopoulos et al 1999, AS 06
+ many others
Gapology
(Ruderman et al, Cheng et al, Romani, Harding)
Resistive MHD / force-free
Li et al 2012, Palenzuela 2012

Magnetospheric models

	Vacuum	Space charge limited	Space charge limited+pairs	Abundant plasma
Field	Rotating vacuum dipole (RVD)	?	Assume RVD	Force-free
Acceleration	wild	gaps	Slot / Outer gaps	none / re-connection?
Spin down	$\frac{2}{3}\frac{\mu^2\Omega^4}{c^3}\sin^2\theta$	?	?	$\frac{\mu^2\Omega^4}{c^3}(1+\sin^2\theta)$
	Ostriker & Gunn 70	Goldreich & Julian 69 Michel 85, 00; AS +Arons 02	Arons 78, Cheng et al 86; Romani et al; Harding et al; Hirotani;	Contopoulos 99; Gruzinov 05; Timokhin 06; AS 06

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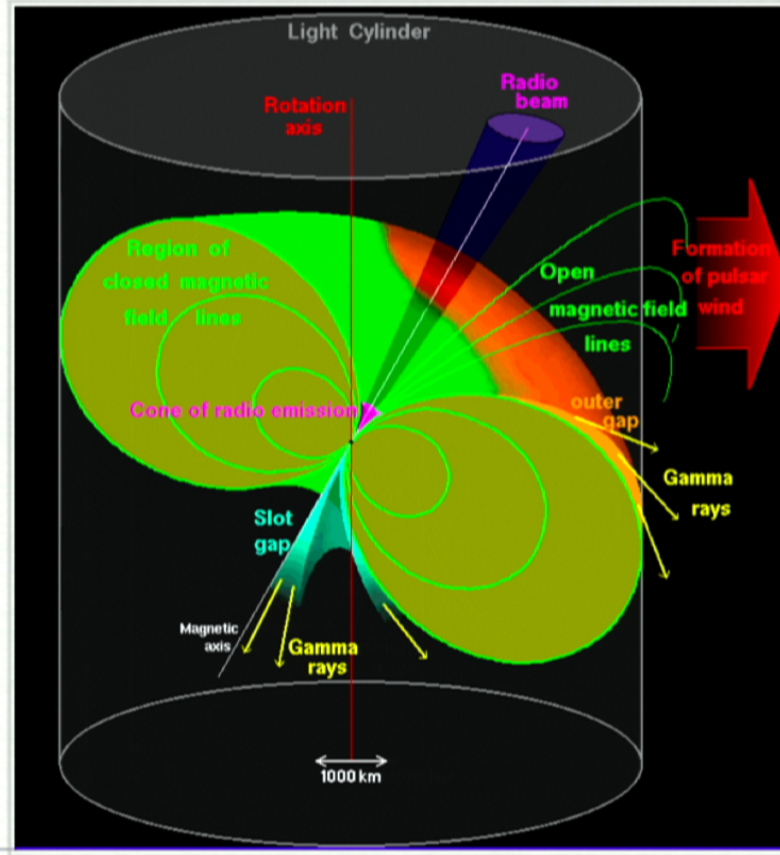
Magnetospheric shape

Several ways of modeling, depending on charge supply:

- Vacuum rotator
- Ab-initio particle
- Full RMHD
- Force-free variants
- "Pulsar equation"



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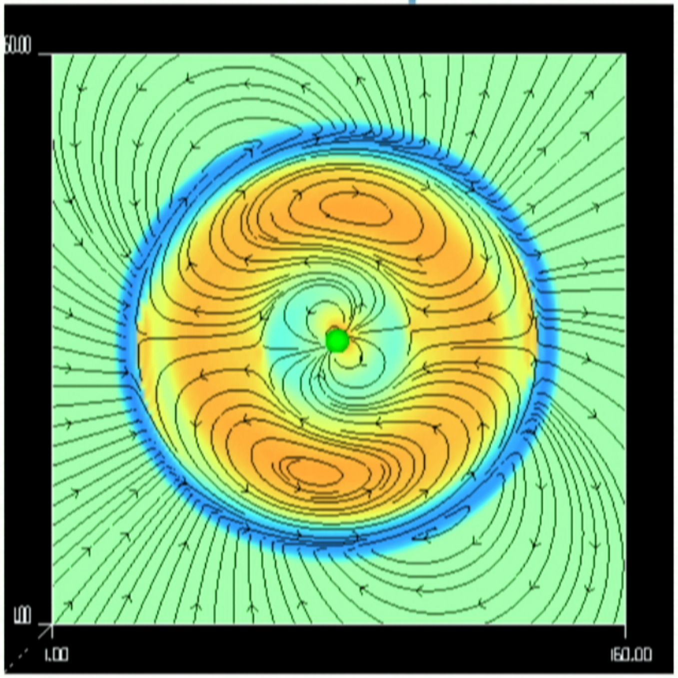

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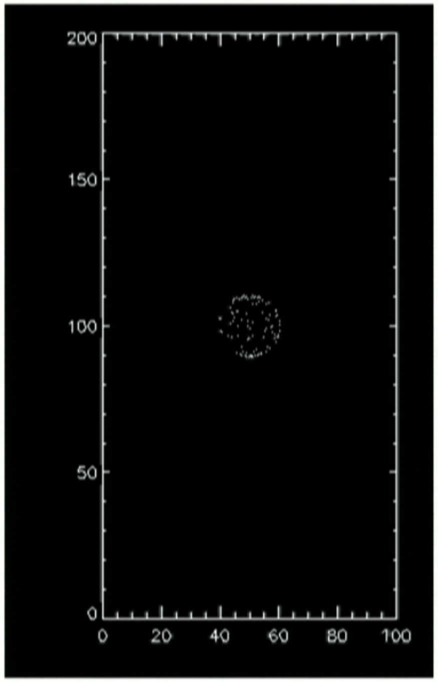
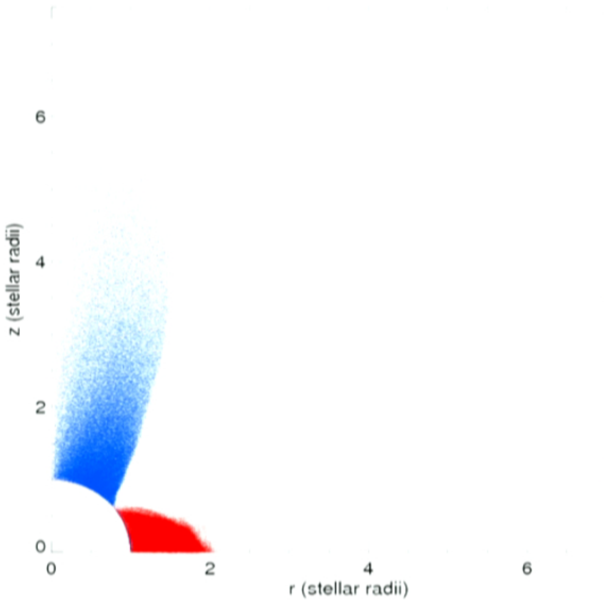
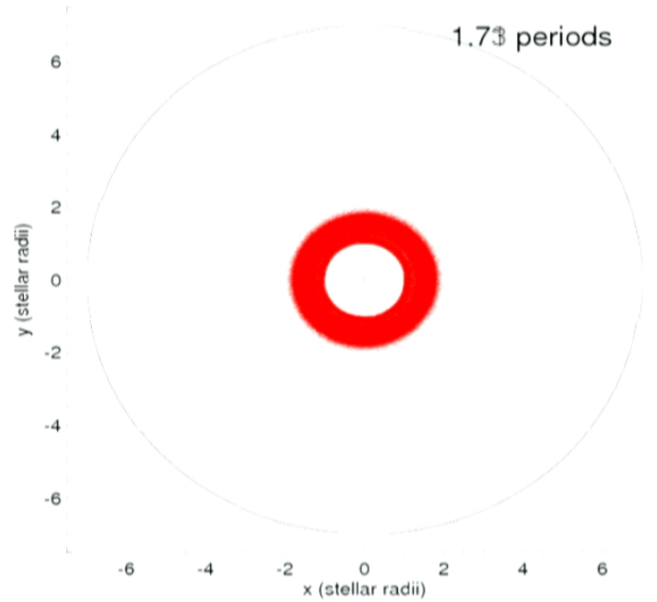


AS & Arons 02;
Michel et al 84, 01

Non-axisymmetric instabilities





Belyaev & AS, in prep

Disk-Torus Electrosphere
Michel et al `84-01

Diocotron instability
AS & Arons 02;
Petri et al 02-


SHK Reebok

Magnetospheric shape

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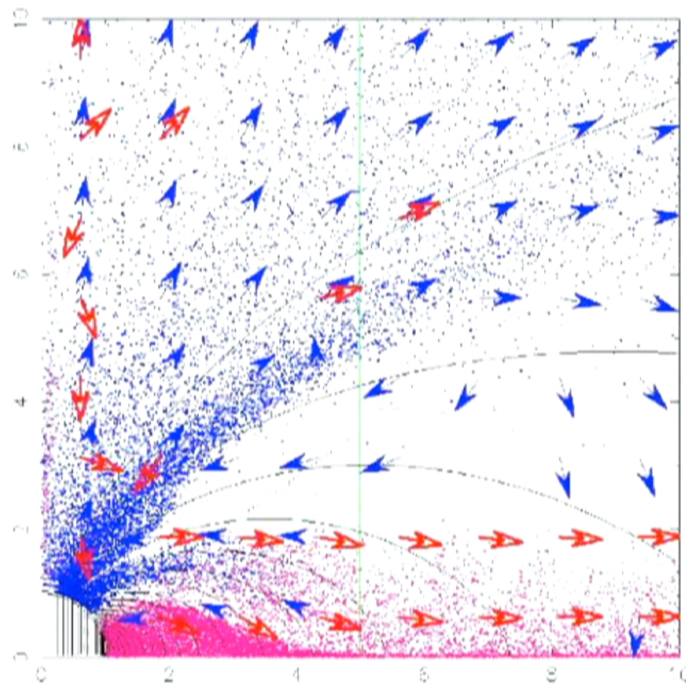

Yuki & Shibata 12

Magnetospheric shape

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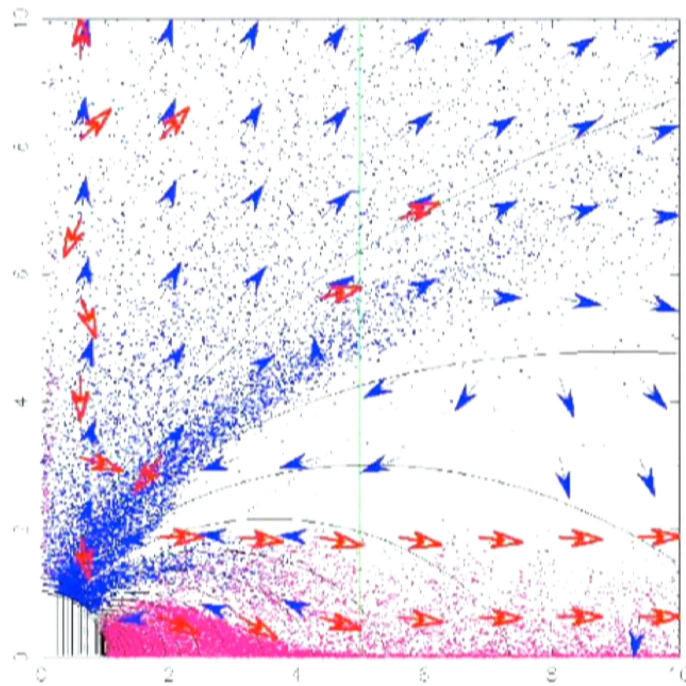

Yuki & Shibata 12

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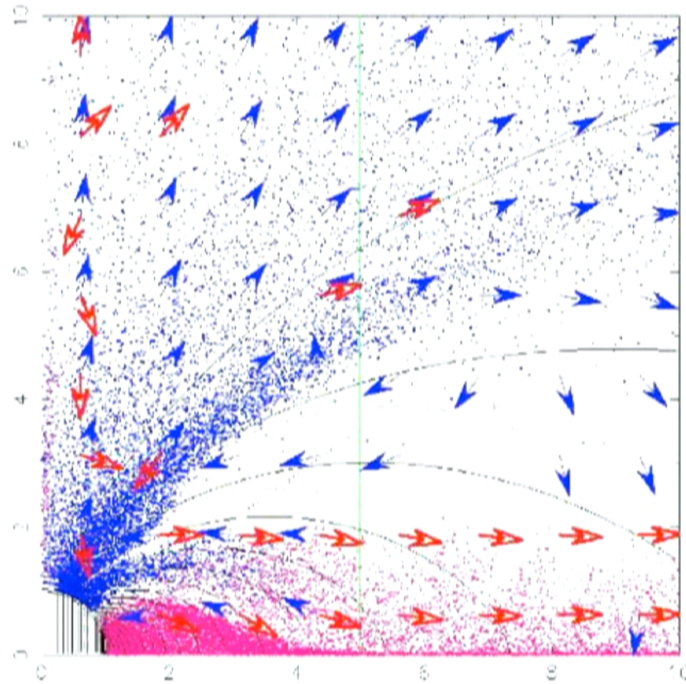

Yuki & Shibata 12

Magnetospheric shape

Several ways of modeling, depending on charge supply:

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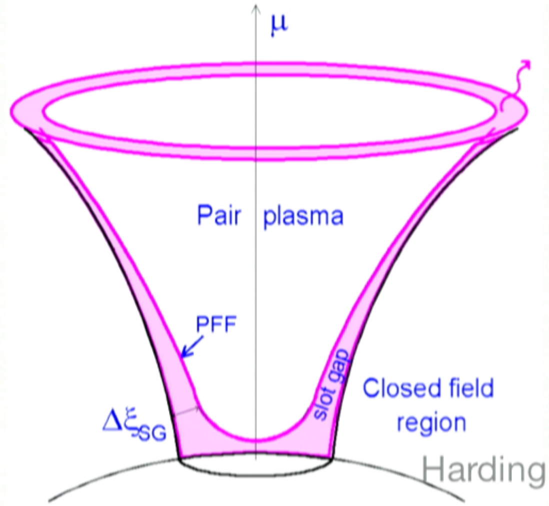
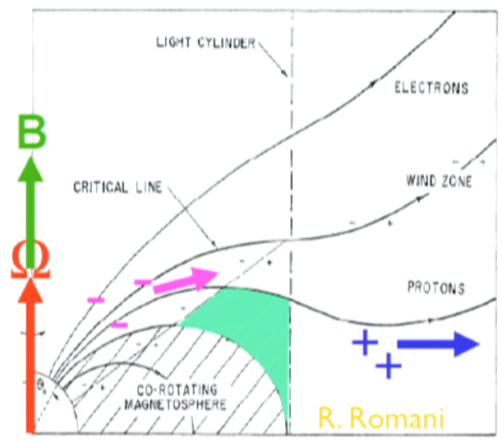
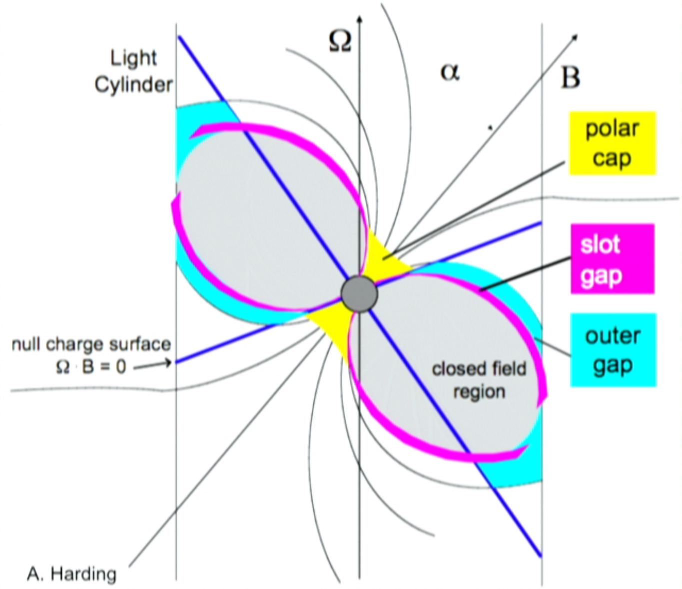
- **Particle/Vacuum+**
- Full RMHD
- Force-free variants
- “Pulsar equation”





Gaps in understanding of gaps...

- Acceleration due to charge starvation
- Gaps imply space-charge separated background flow, even though pairs are created.
- PWNe require pair densities >> minimum charge separated density.



Harding

Gap models are best developed but are not self-consistent.

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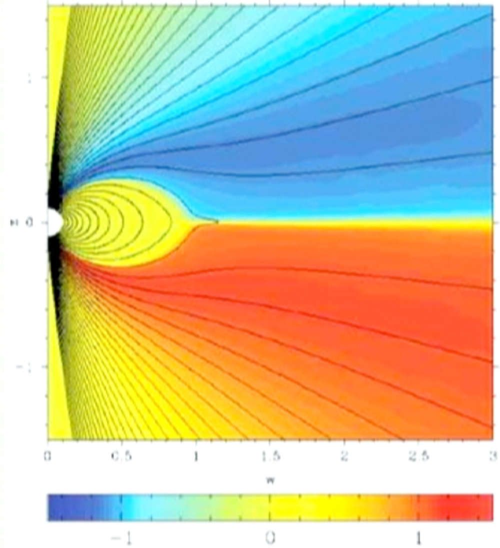

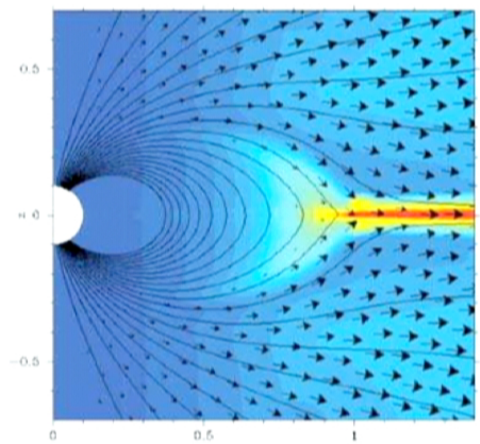

Komissarov 06

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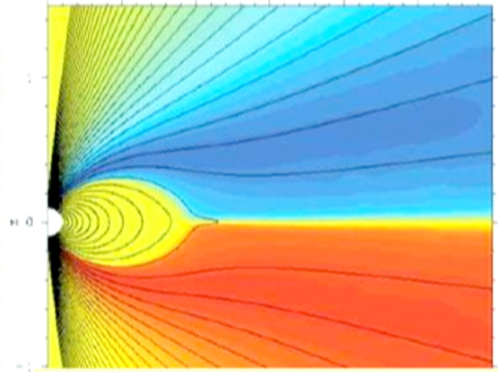
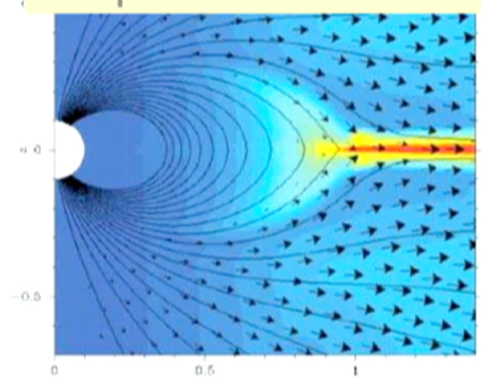


High magnetization near the star is difficult to simulate with MHD. Require simplification: force-free



Komissarov 06

Methods for solution: Relativistic MHD

Conditions:

$$v \simeq c, \quad v_a \simeq c,$$

Equations:

$$\nabla_\beta \left(T^{\alpha\beta}_{(m)} + T^{\alpha\beta}_{(f)} \right) = 0$$

$$\nabla_\beta {}^*F^{\alpha\beta} = 0$$

$$\nabla_\alpha (n u^\alpha) = 0$$

$$F_{\nu\mu} u^\mu = 0$$ *- perfect conductivity*

$$T^{\alpha\beta}_{(f)} = F^{\alpha\gamma} F^\beta_\gamma - \frac{1}{4}(F_{\mu\nu}F^{\mu\nu}) g^{\alpha\beta}$$ *-stress-energy-momentum of electromagnetic field*

-stress-energy-momentum of matter

$$T^{\alpha\beta}_{(m)} = w u^\alpha u^\beta + p g^{\alpha\beta}$$

Full MHD vs force-free

Conditions:

$$v \simeq c, \quad v_a \simeq c,$$

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$$T^{\alpha\beta}_{(m)} = w u^\alpha u^\beta + p g^{\alpha\beta}$$

Conditions:

$$T^{\alpha\beta}_{(m)} \ll T^{\alpha\beta}_{(ef)}$$

Equations:

$$\nabla_\mu \boldsymbol{T}^{\nu\mu}_{(f)} = 0$$

$$\nabla_\beta \, {}^*F^{\alpha\beta} = 0$$

$$F_{\mu\nu} \, {}^*F^{\mu\nu} = 0$$

$$F_{\mu\nu} F^{\mu\nu} > 0$$

or

$$\boldsymbol{E} \cdot \boldsymbol{B} = 0$$

$$B^2 - E^2 > 0$$

(Komissarov 2002)

Force-free equations

Full RMHD equations become stiff for high magnetization

$$mn\frac{\partial\gamma\vec{v}}{\partial t} = \rho\vec{E} + \frac{\vec{j}}{c}\times\vec{B} \approx 0$$

Derive dynamical set of equations by ignoring particle inertia but retaining plasma charges and currents.

$$\left.\begin{aligned}
\frac{1}{c}\frac{\partial E}{\partial t} &= \nabla\times\vec{B} - \frac{4\pi}{c}\vec{j} \\
\frac{1}{c}\frac{\partial B}{\partial t} &= -\nabla\times\vec{E} \\
\rho\vec{E} + \frac{\vec{j}}{c}\times\vec{B} &= 0 \\
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\end{aligned}\right\} \quad \vec{j} = \frac{c}{4\pi}(\nabla\cdot\vec{E})\frac{\vec{E}\times\vec{B}}{B^2} + \frac{c\vec{B}(\vec{B}\cdot\nabla\times\vec{B} - \vec{E}\cdot\nabla\times\vec{E})}{4\pi B^2}$$

"Force-free MHD"

Gruzinov 99, Blandford 01

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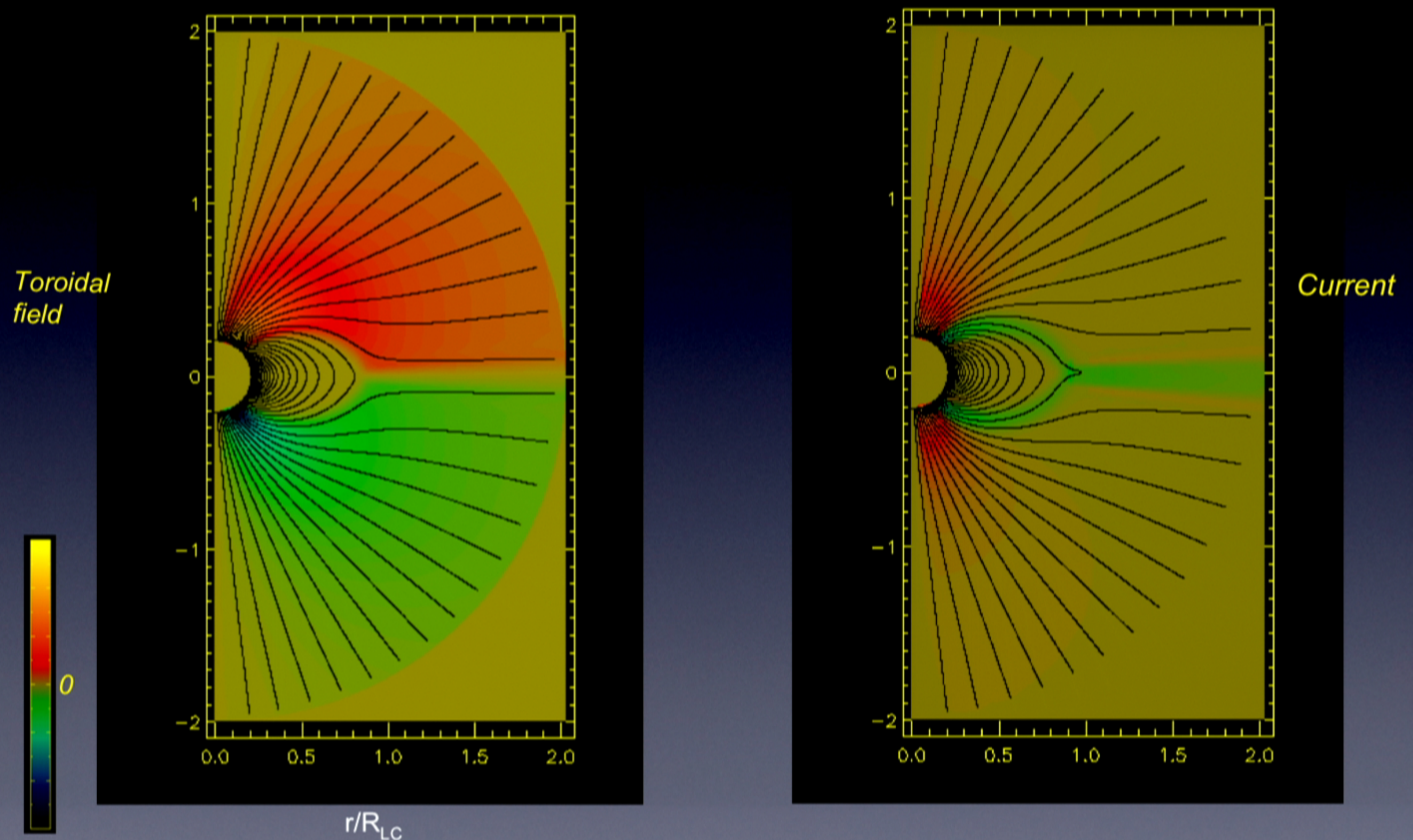
Aligned rotator: plasma magnetosphere



Properties: current sheet, split-monpolar asymptotics; closed-open lines; Y-point; null charge surface is not very interesting. Now at least 6 groups can do this (recently, Yu 11, Parfrey 11, Petri 12, Palenzuela 12, in addition to AS 06, McKinney 06, Kalapotharakis 09)

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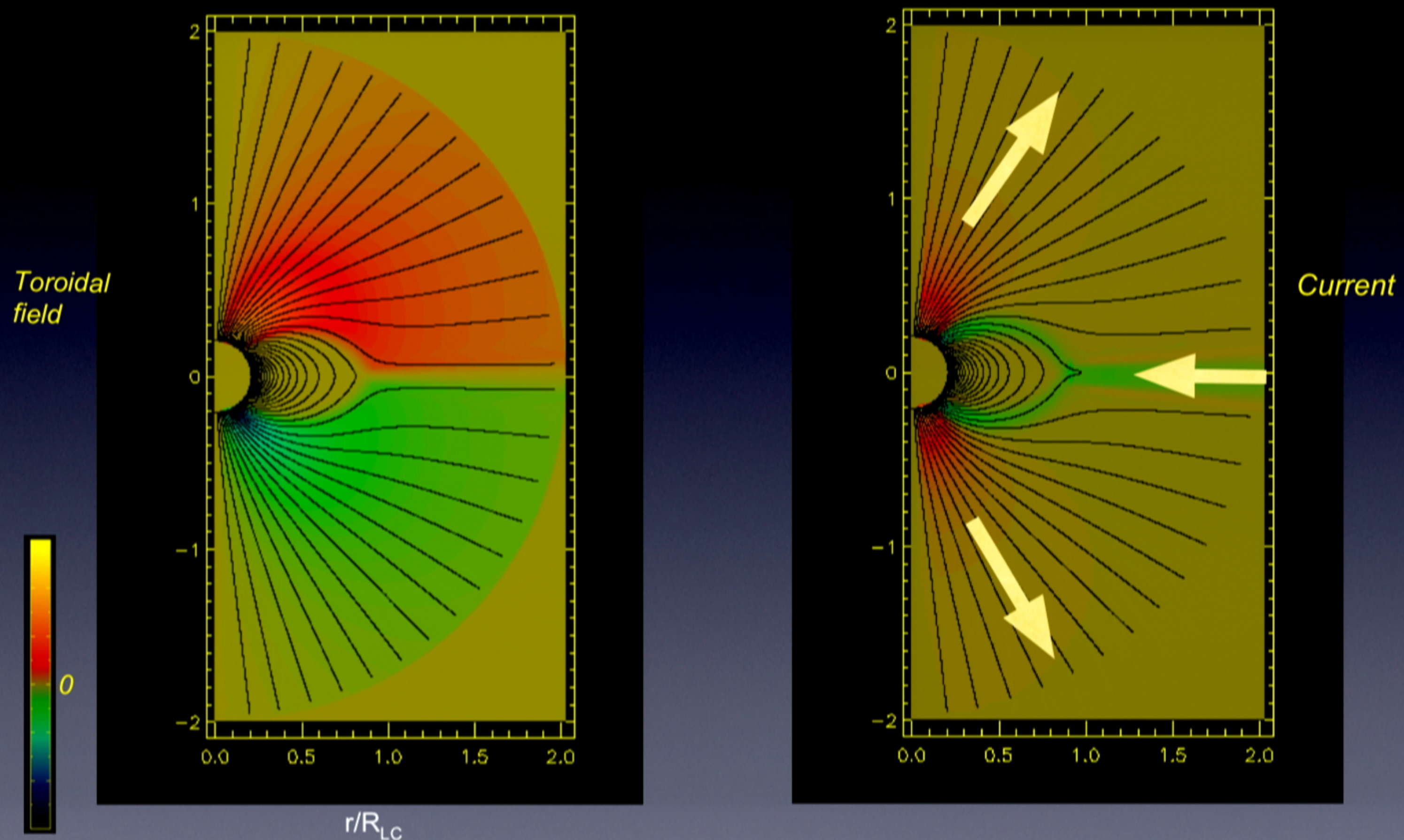

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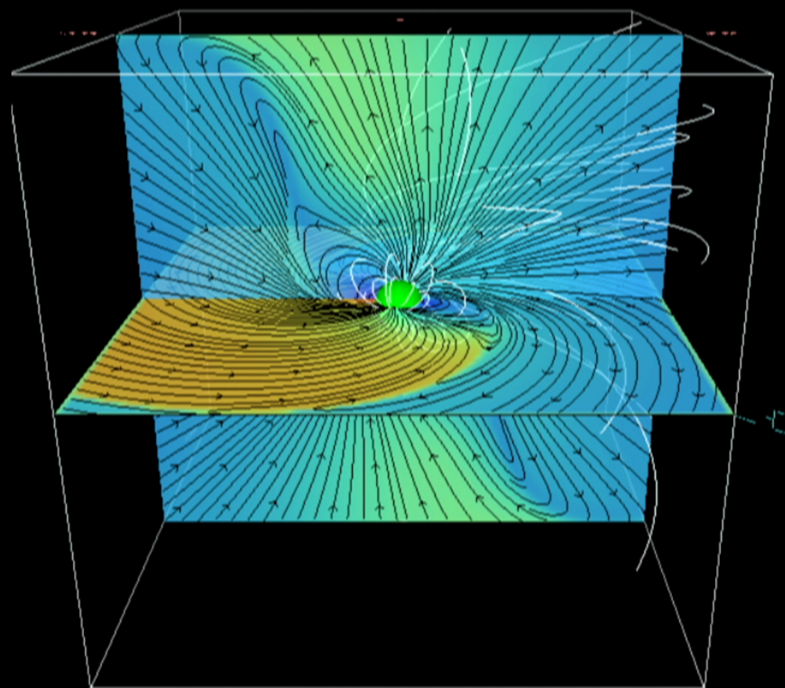
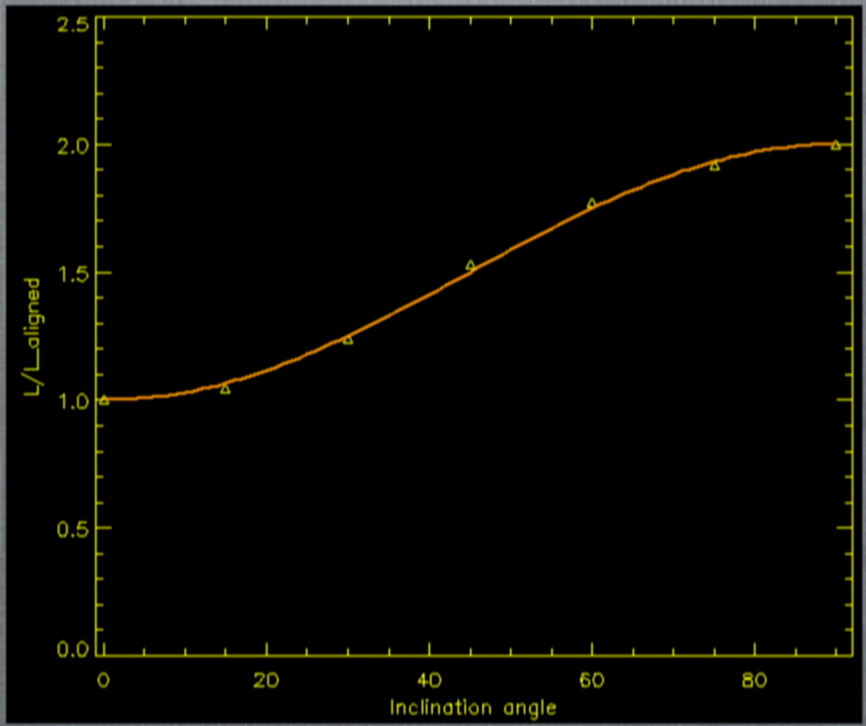
Oblique rotator: force-free



A.S. 2006

SPIN-DOWN POWER



Spin-down of oblique rotator

NB: this is a fit!

$$\dot{E} = \frac{\mu^2\Omega^4}{c^3}(1+\sin^2\theta)$$

$$\dot{E}_{vac} = \frac{2}{3}\frac{\mu^2\Omega^4}{c^3}\sin^2\theta$$

A.S.'06; also confirmed by Kalapotharakos & Contopoulus 09

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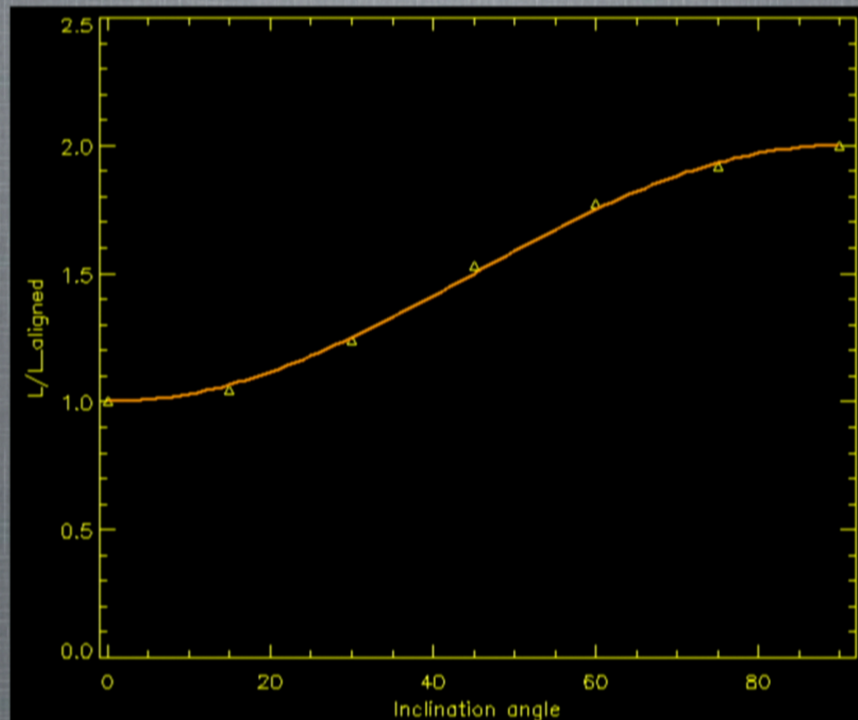

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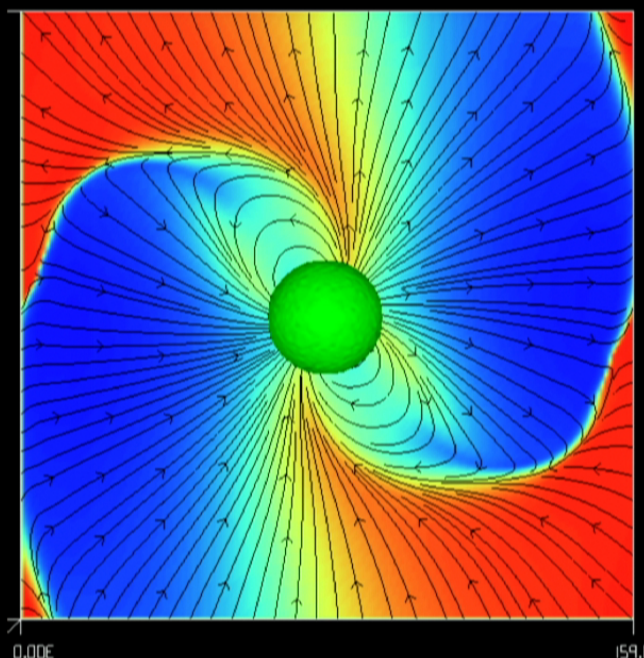
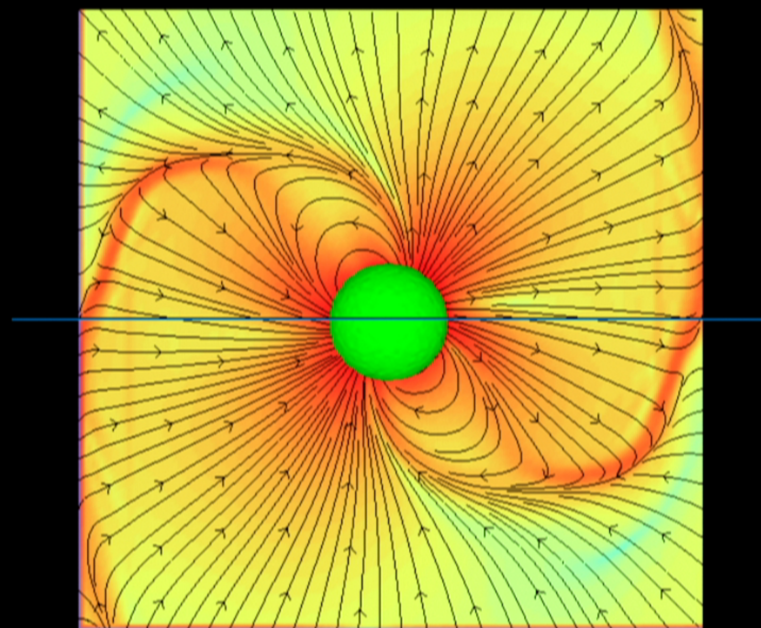
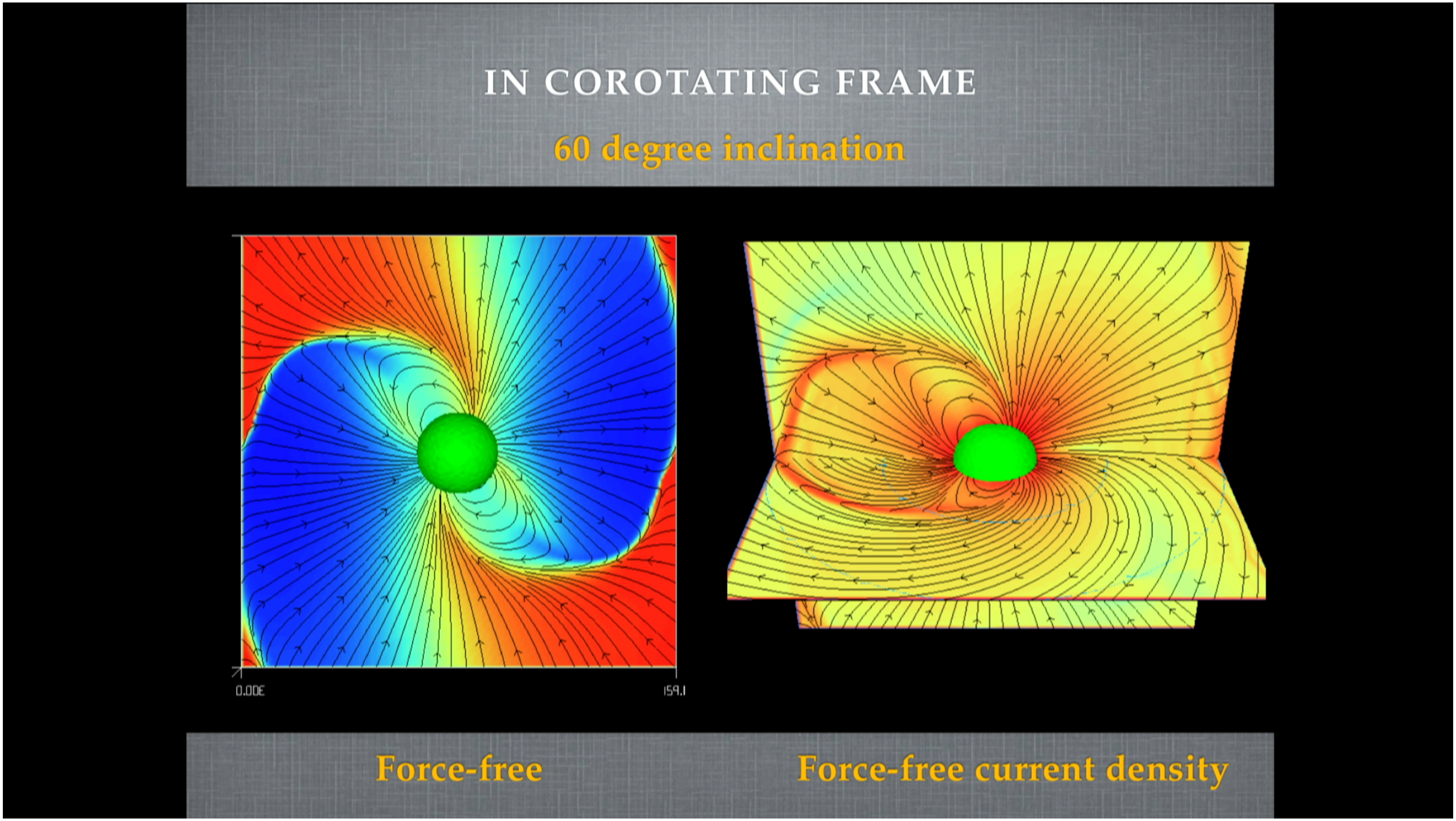
IN COROTATING FRAME

60 degree inclination





Force-free | **Force-free current density**


IN COROTATING FRAME
60 degree inclination
0.00E
159.1
Force-free
Force-free current density

IN COROTATING FRAME

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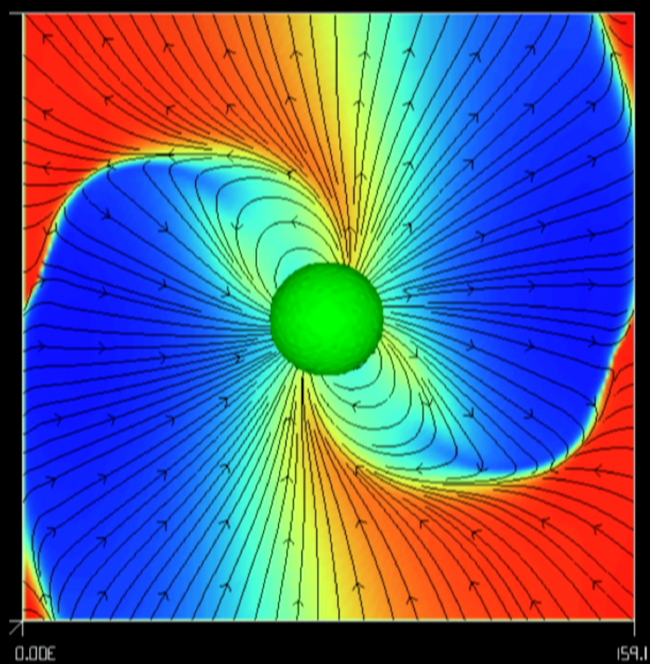
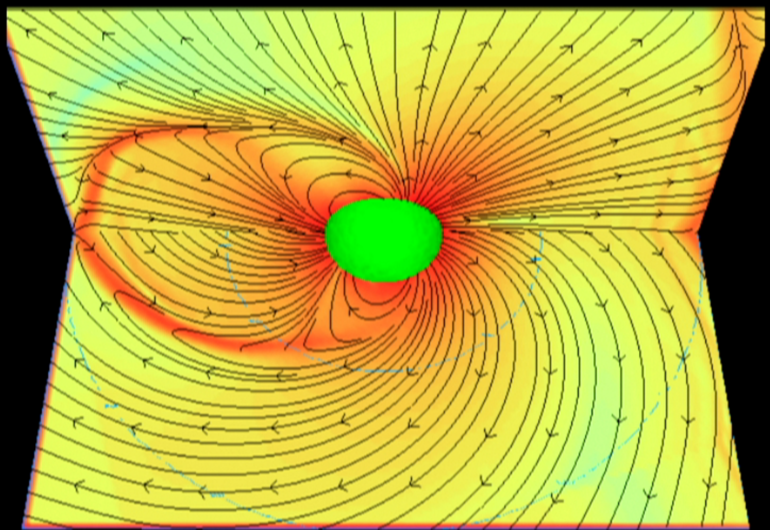


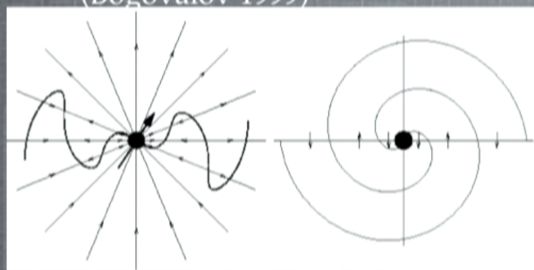


Force-free **Force-free current density**

Implications

Force-free pulsar solution

Split-monopole:
(Bogovalov 1999)



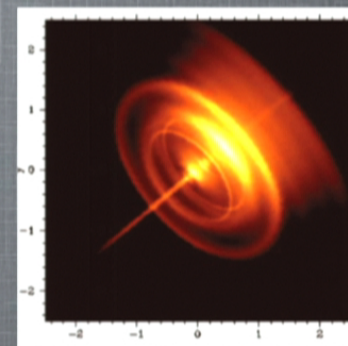
Heliospheric current sheet

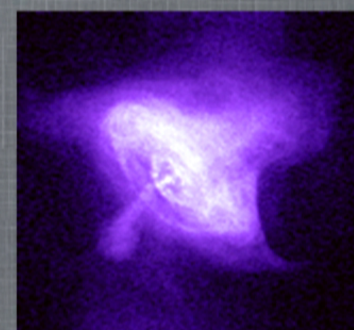
Simulations of PWN require latitude-dependent energy injection, which is naturally provided by the model with reconnecting reversing fields in the equatorial zone.

$$B_\varphi \propto \sin\theta\left(1-\frac{2\theta}{\pi}\right)$$

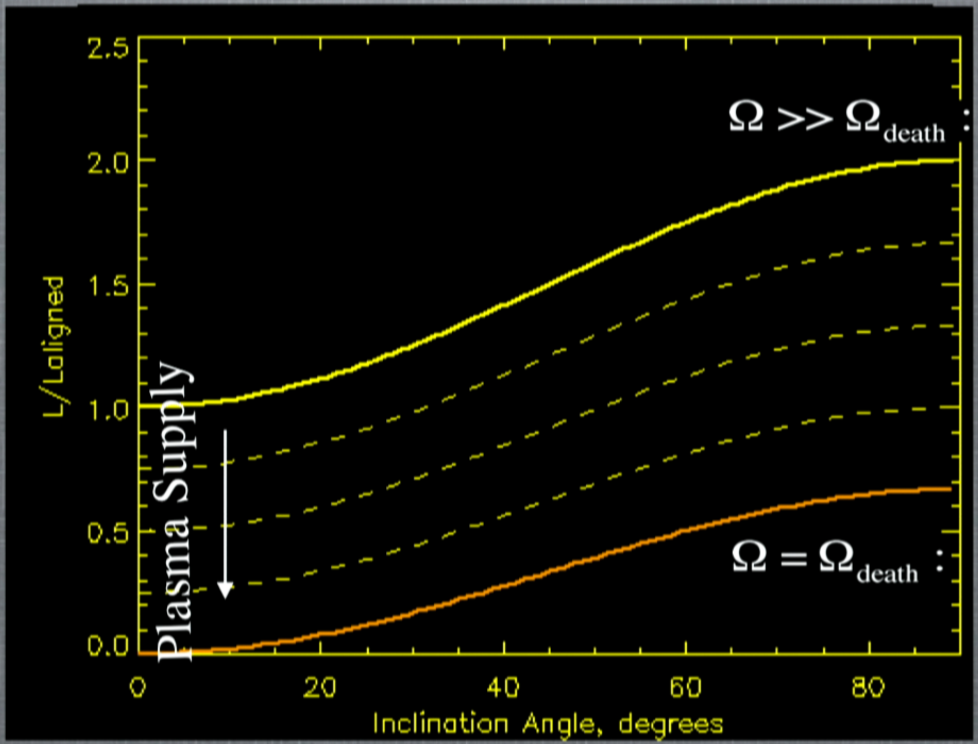
Poynting flux is distributed as $\sin^2\theta$ in force-free models (θ-polar angle)

Komissarov & Lyubarsky





SPIN-DOWN POWER



We expect a continuum of solutions that depend on plasma supply. These can be characterized by the presence of accelerating E field, or resistivity.

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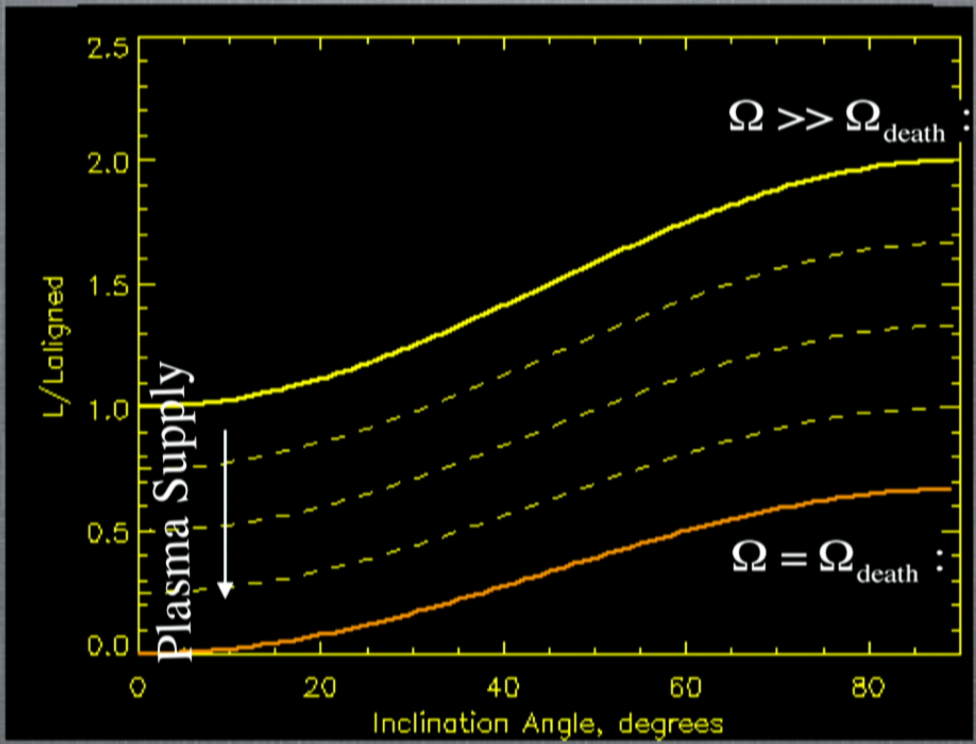

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Resistive force-free

- There is a continuum of solutions between vacuum and ideal conducting force-free magnetosphere if plasma is not perfect everywhere.
- Can parameterize these with resistivity in the proper frame.
- Nice feature: re-emergence of parallel E field.

Ohm's law in the proper frame:

$$\vec{j}_{\rm fluid} = \sigma \vec{E}_{\rm fluid}$$

In lab frame:

$$\vec{j} = \frac{\rho c \vec{E}\times\vec{B}}{B^2+E_0^2} + \frac{(-\beta_{||}\rho c + \sqrt{\frac{B^2+E_0^2}{B_0^2+E_0^2}}(1-\beta_{||}^2)\sigma E_0)(B_0\vec{B}+E_0\vec{E})}{B^2+E_0^2}$$

$$B_0^2 = \frac{\vec{B}^2-\vec{E}^2+\sqrt{(\vec{B}^2-\vec{E}^2)^2+4(\vec{E}\cdot\vec{B})^2}}{2},$$

$$E_0 = \sqrt{B_0^2-\vec{B}^2+\vec{E}^2},$$

$$B_0 = \mathrm{sign}(\vec{E}\cdot\vec{B})\sqrt{B_0^2},$$

cf. Lyutikov 03
Gruzinov 07-11

Li, AS, Tchekhovskoy, 2011

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Minimal || velocity frame:

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$$B_0^2 = \frac{\vec{B}^2 - \vec{E}^2 + \sqrt{(\vec{B}^2 - \vec{E}^2)^2 + 4(\vec{E}\cdot\vec{B})^2}}{2},$$

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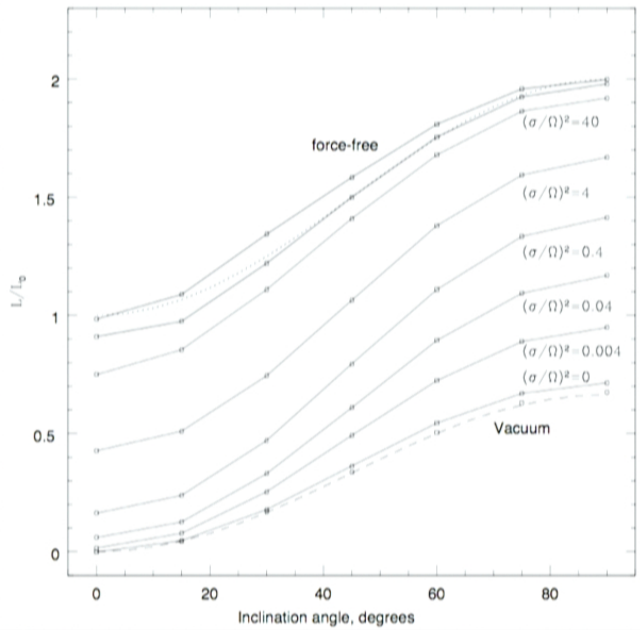
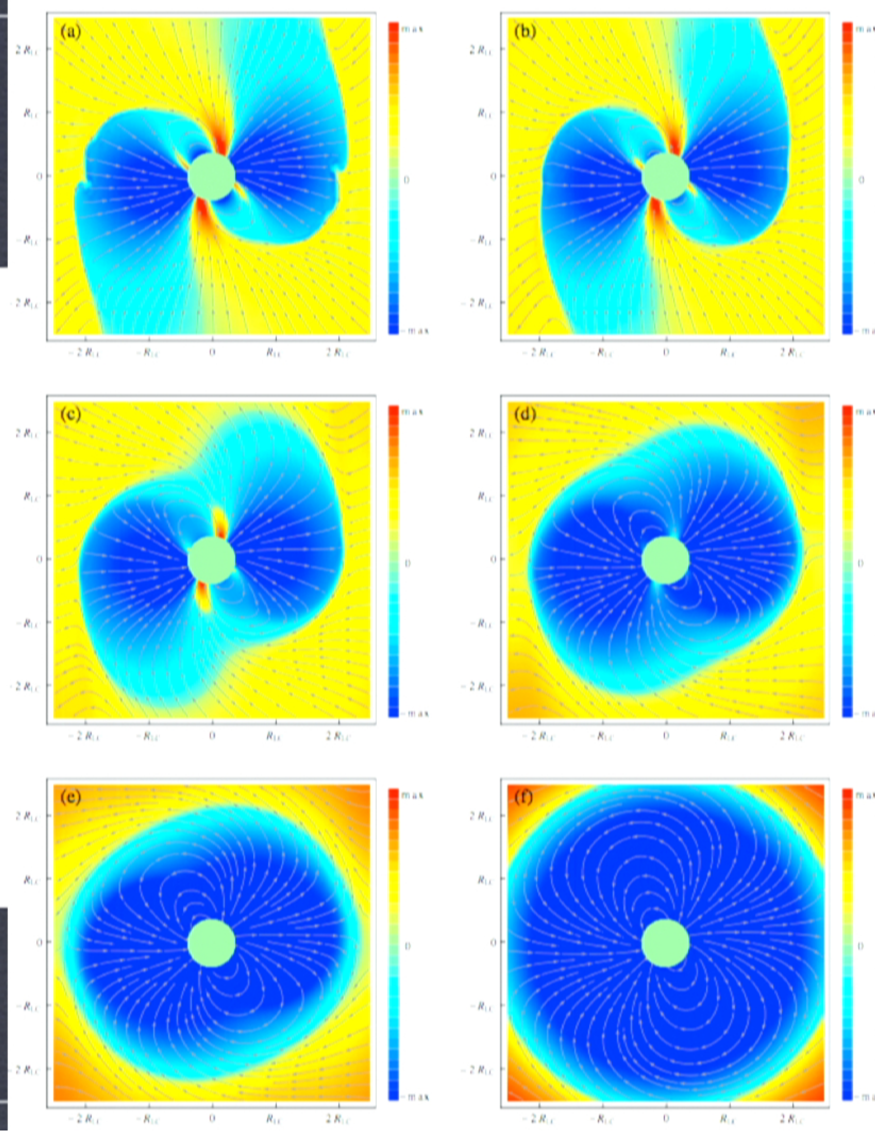
Li, AS, Tchekhovskoy, 2011
also, Kalapotharakos et al 11

Resistive:

Vary σ/Ω





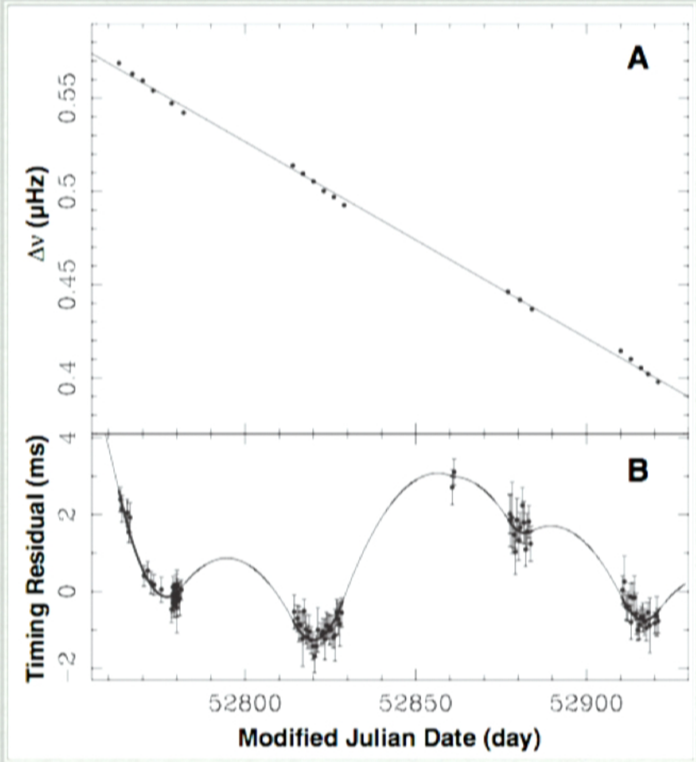
Spin-down power

Li, AS, Tchekhovskoy 12

Application: intermittent pulsars

- Intermittent pulsars display changes in spin-down power when they are ON and OFF in radio by factor >1.5

- One possibility: conducting closed zone, vacuum-like open zone; Interrupted plasma production



Kramer et al 06

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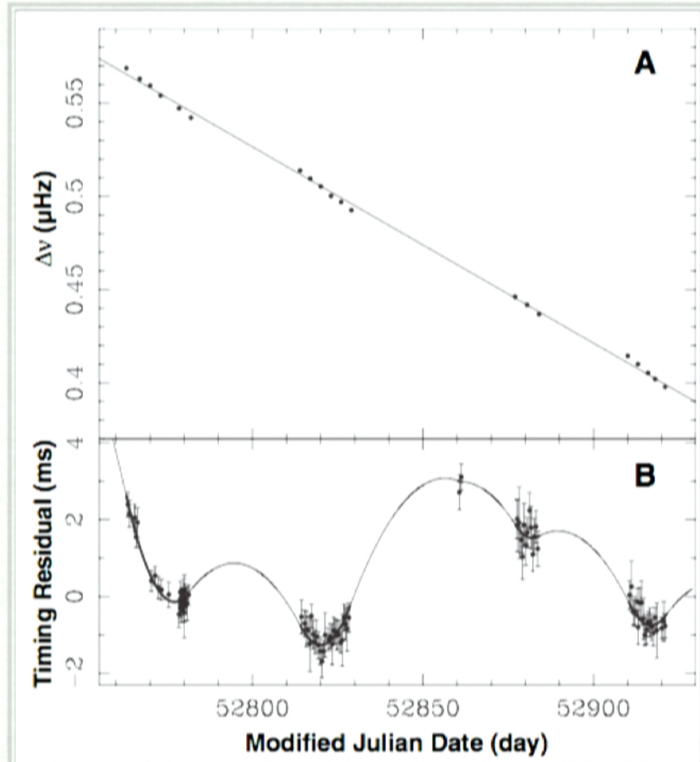
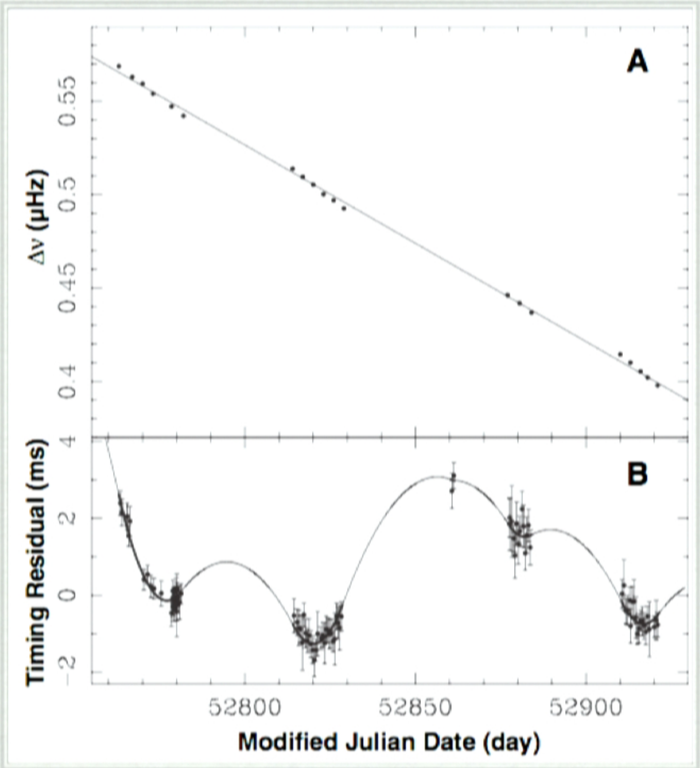


Kramer et al 06

Application: intermittent pulsars

- Intermittent pulsars display changes in spin-down power when they are ON and OFF in radio by factor >1.5
- One possibility: conducting closed zone, vacuum-like open zone; Interrupted plasma production



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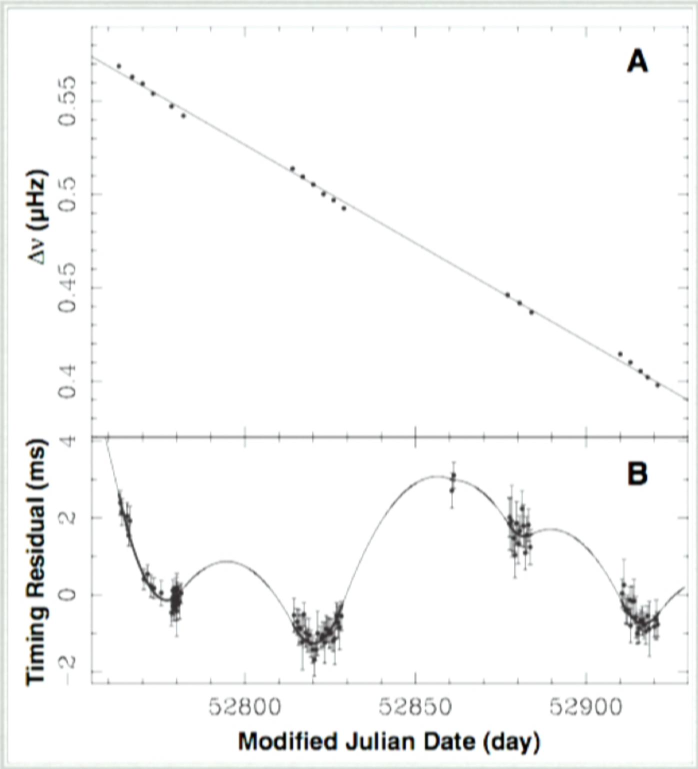

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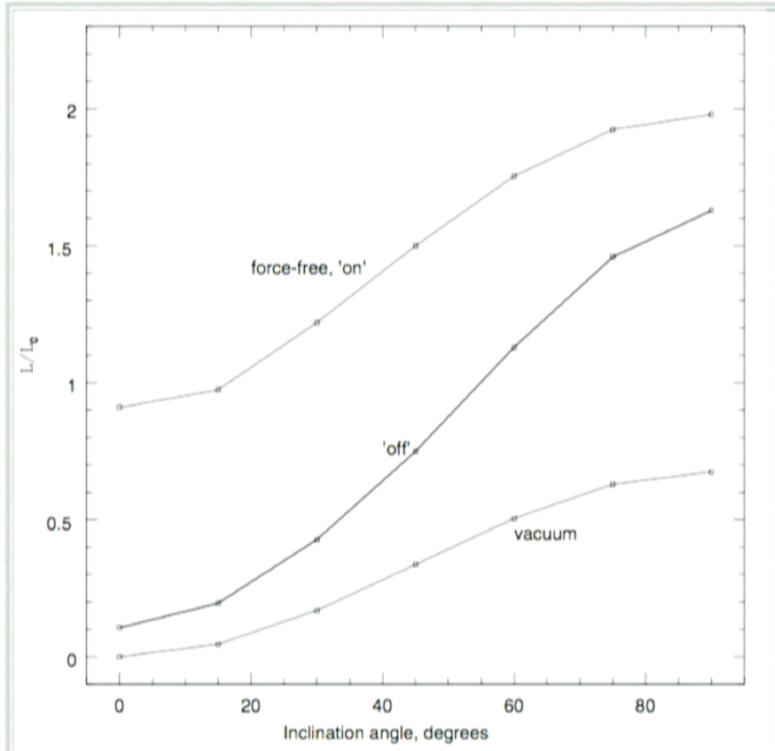

Li et al 12

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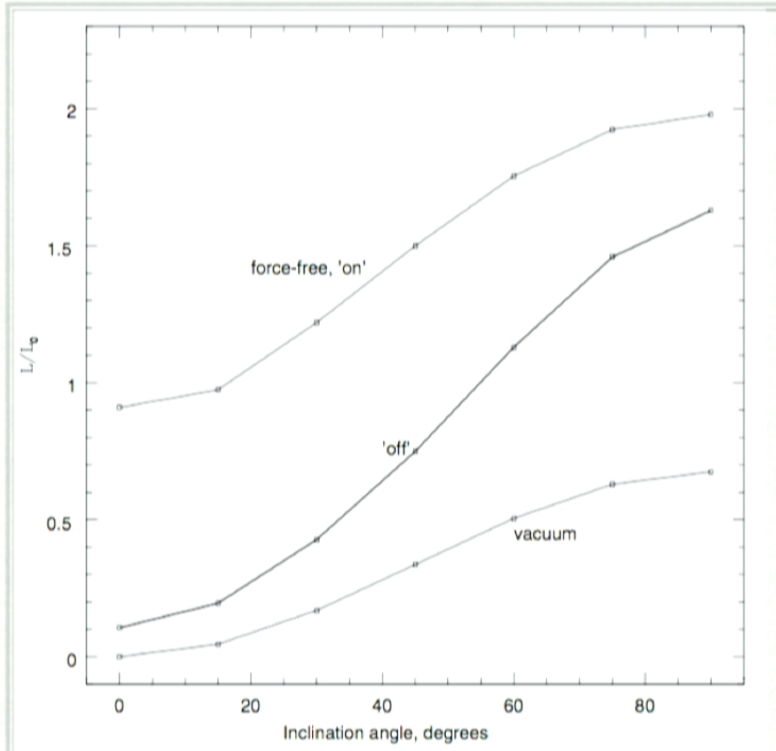

Li et al 12

Recent advances:

- Full RMHD is now in 3D!
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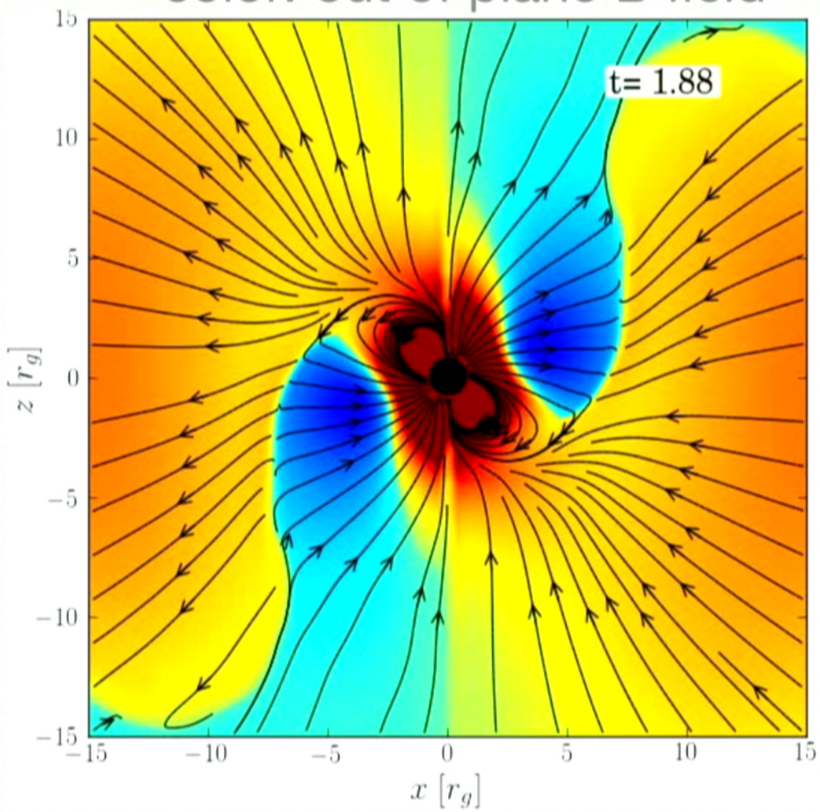
color: out of plane B field



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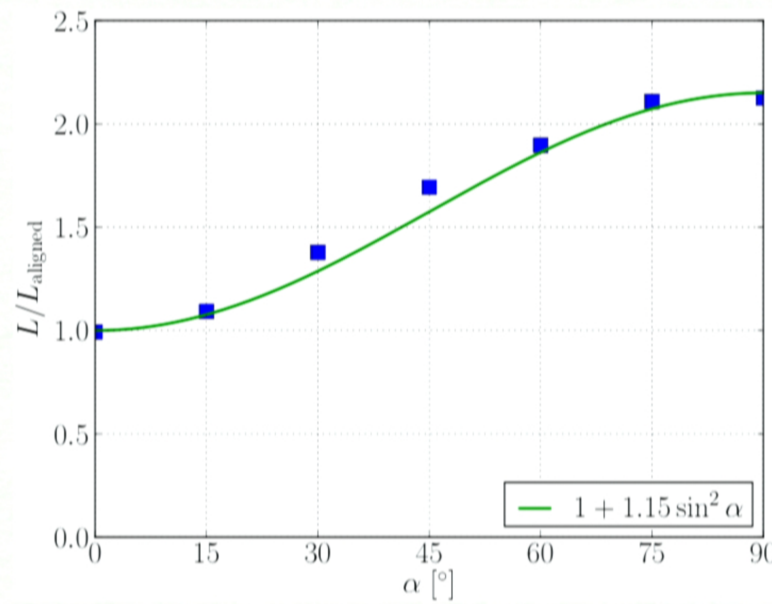
Spin down luminosity



Obliqueness

Variation with angle is similar to force-free

Recent advances:

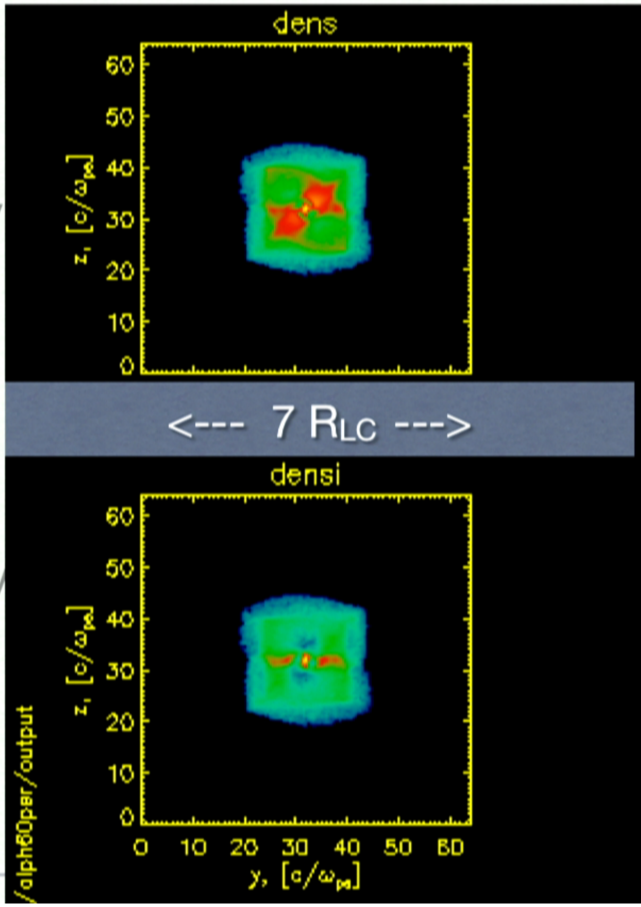
Vacuum field + test particles

- Full particle modeling with PIC (particle-in-cell) in 3D (AS in prep).
- Idea: supply enough neutral plasma and "let it figure it out."
- $E = E_{plasma} + E_{Deutsch}$; $B = B_{plasma} + B_{Deutsch}$

Step 1: Test electrons & ions become distributed in different locations -- no clear sheet

Full density

Ion density



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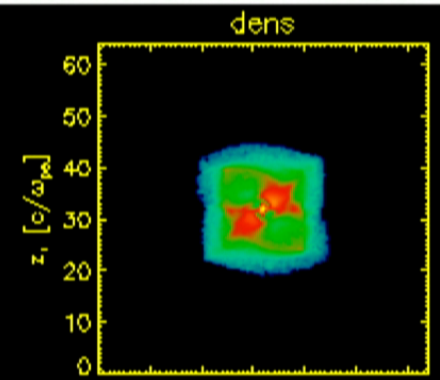

<--- 7 R_{LC} --->

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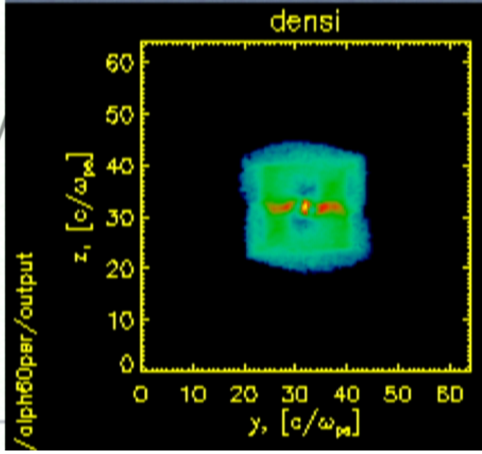

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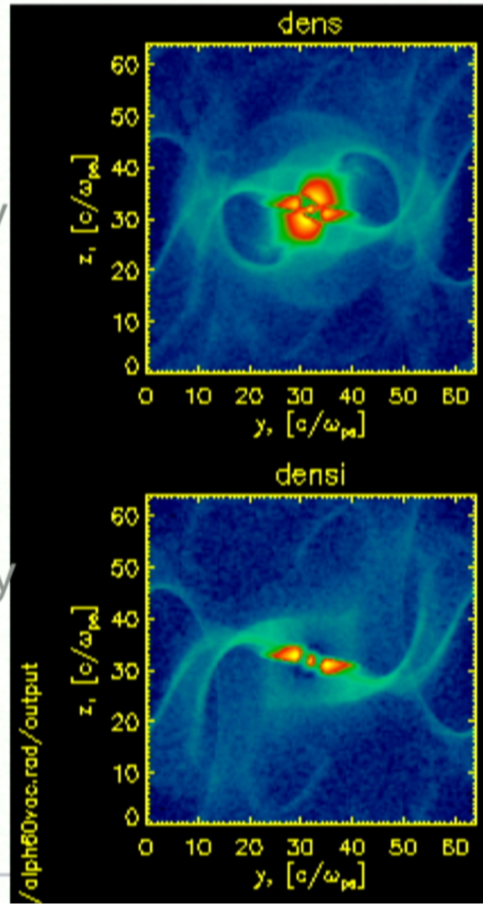

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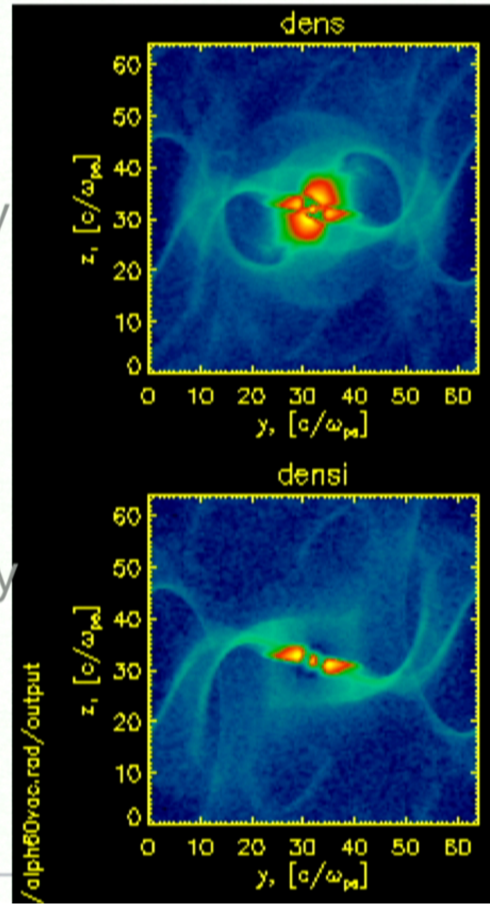

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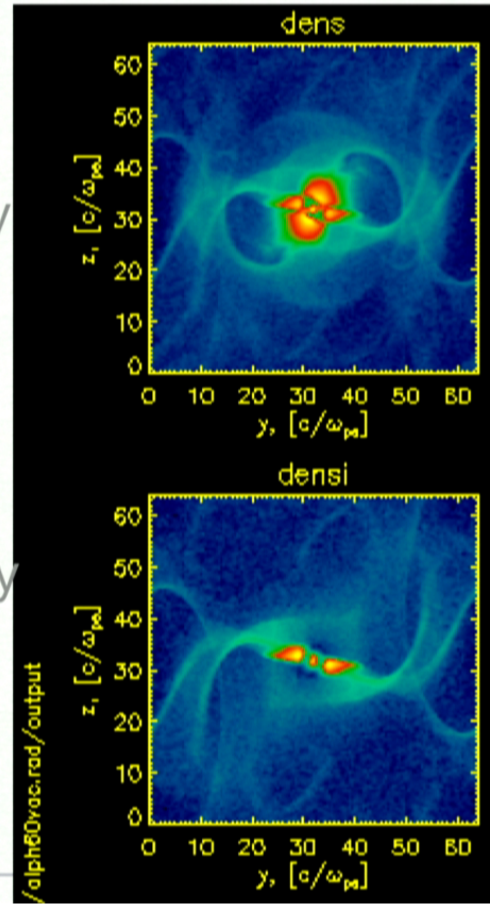


Test electrons & ions become distributed in different locations -- no clear sheet

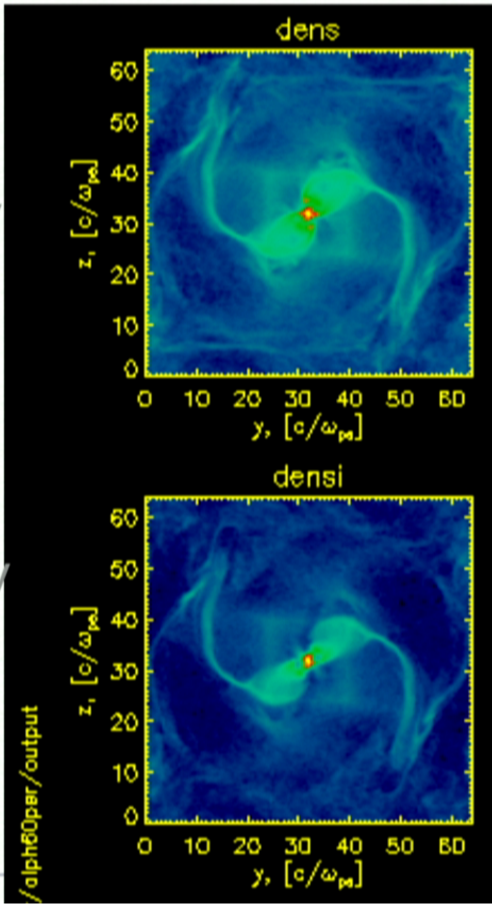
Recent advances:

Vacuum field + plasma

- Full particle modeling with PIC (particle-in-cell) in 3D.
- Turn on plasma back reaction:

Full density

Ion density



Electrons & ions now are together and form a current sheet. Approaches force-free.

Recent advances:

Vacuum field + plasma

- In principle, such a solution has everything: acceleration, plasma velocity, reconnection.
- In practice the resolution will always be limited.
- Also, the aligned rotator part depends on good BCs on the star -- still in progress.

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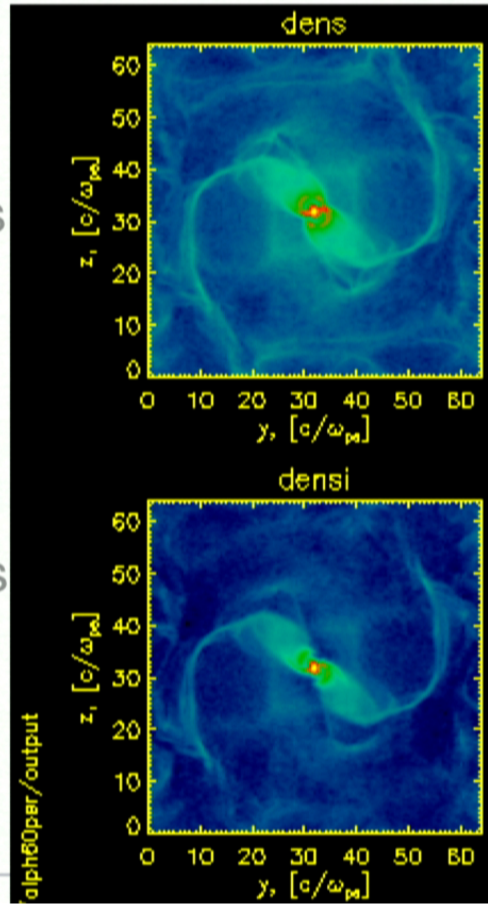

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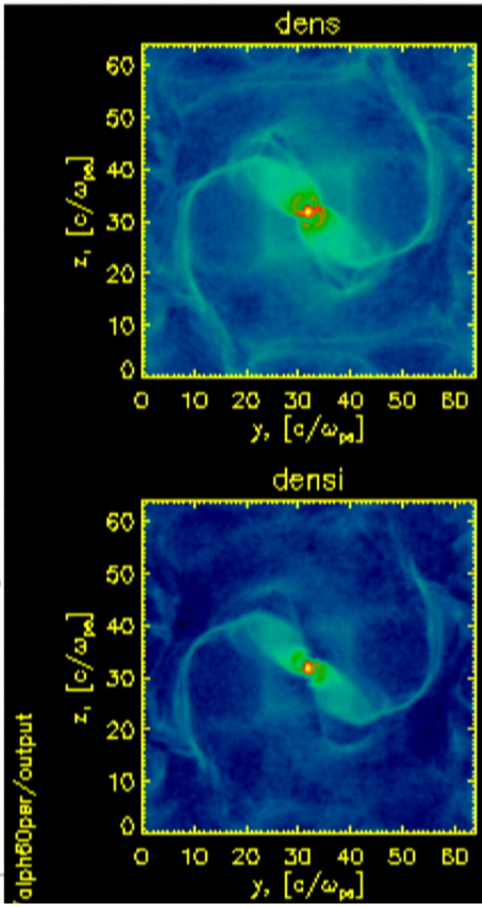
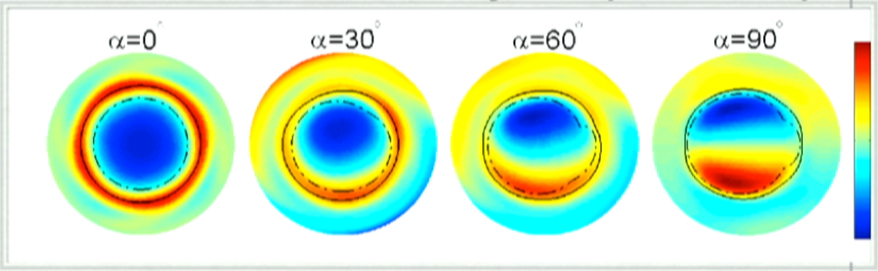


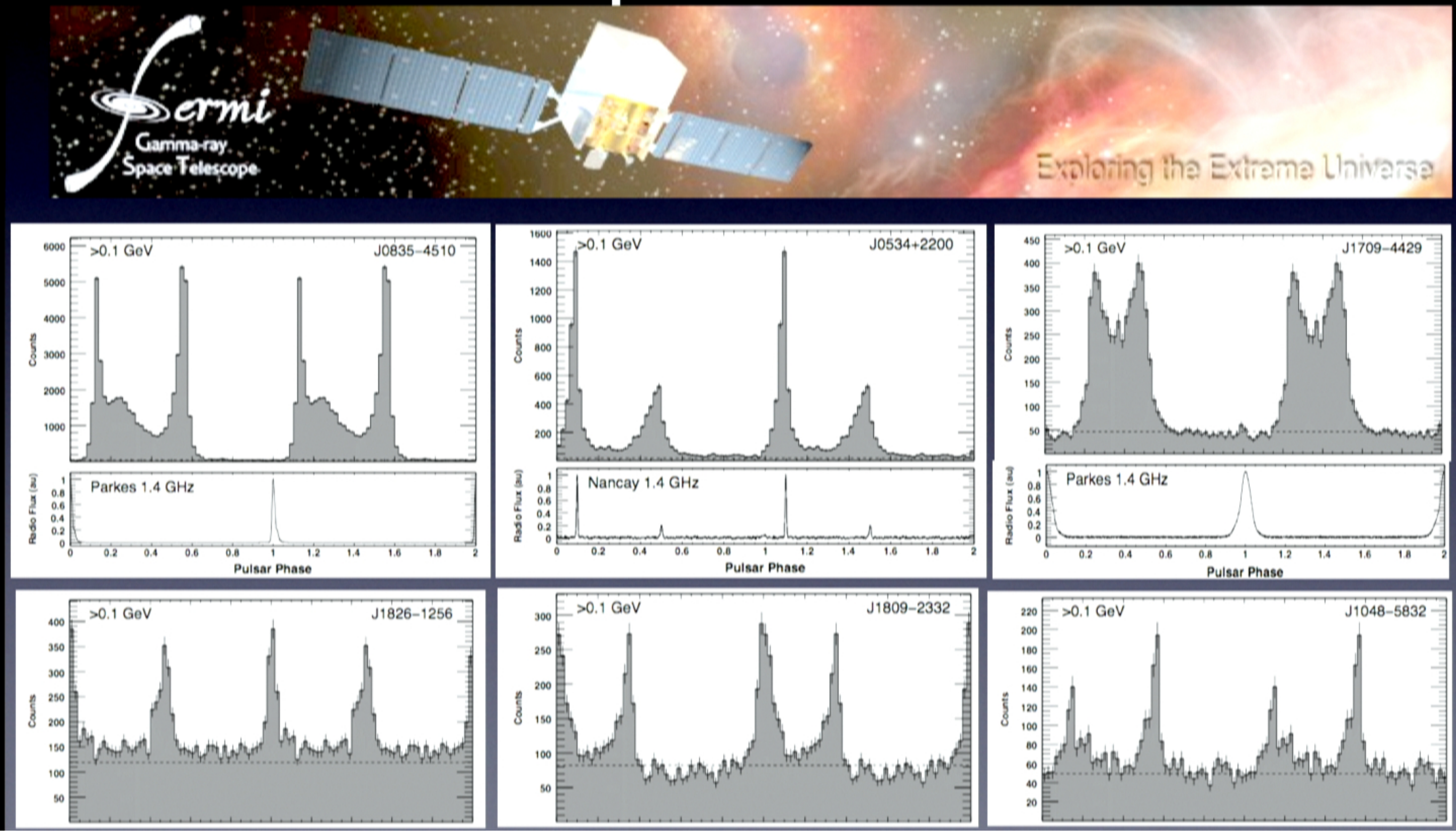
Where does emission come from?

- With force-free shape of the magnetosphere at hand, emission physics can be studied again.
- Most progress so far is on the geometry of the emission so far (gamma-rays).
- Does the emission come from gap regions? Inside or outside LC?

Current density on polar cap



Gamma-ray emission from pulsars



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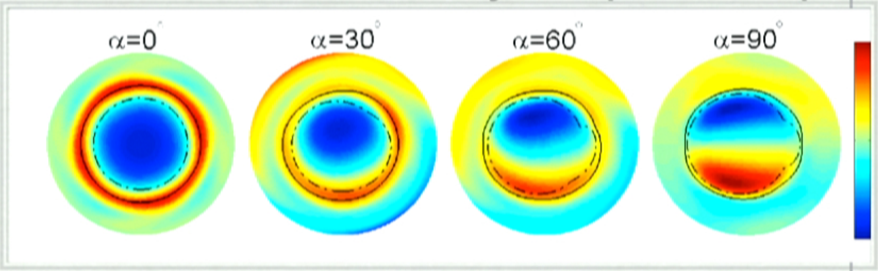

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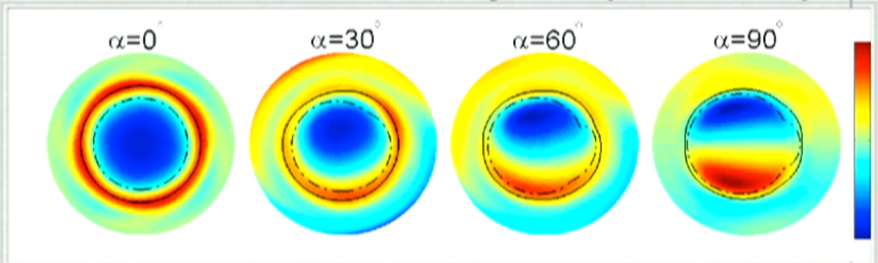

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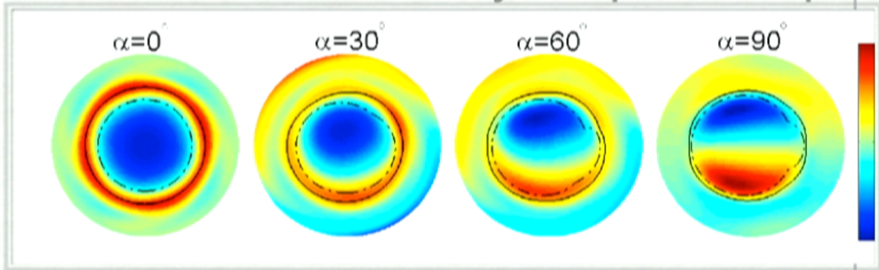

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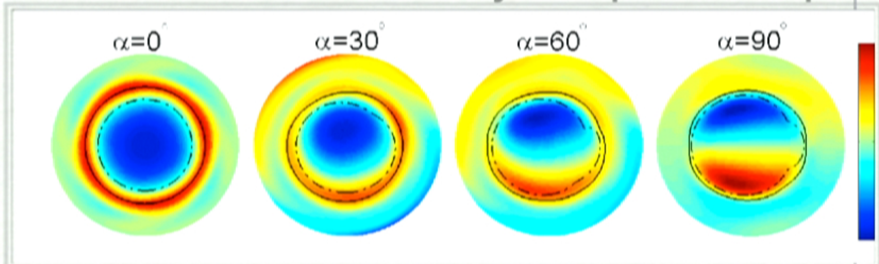

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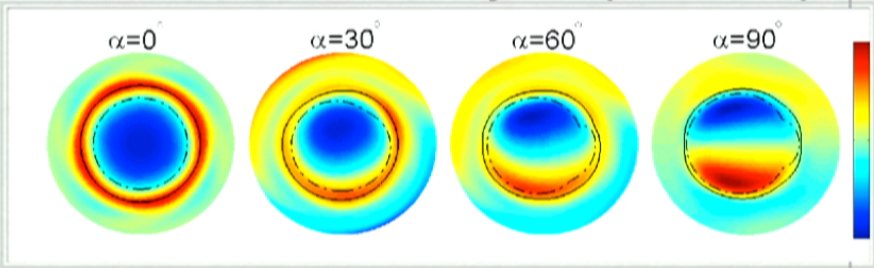

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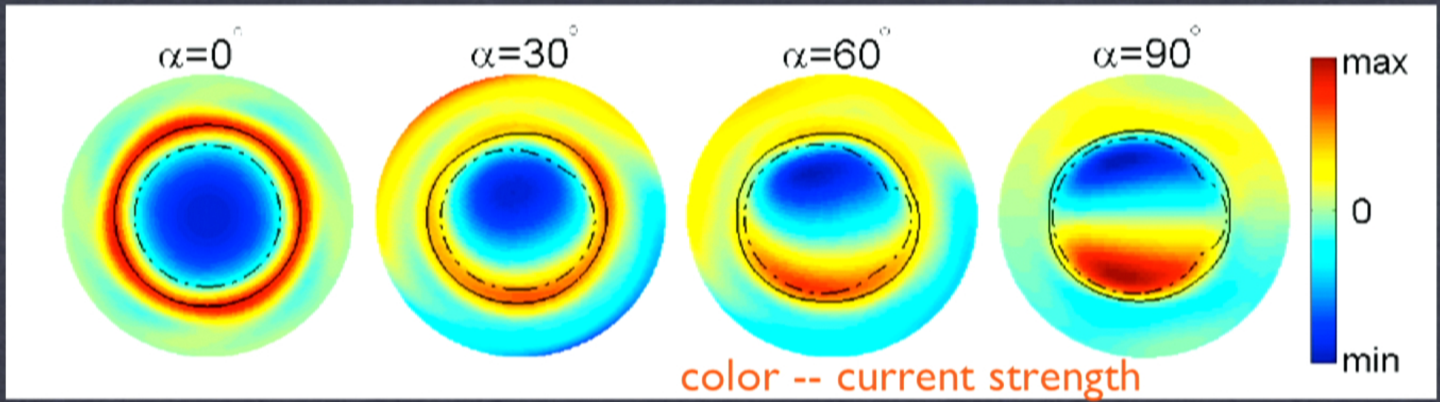

- Select flux tubes that map into rings on the polar caps. The rings are congruent to the edge of the polar cap.

- While ad-hoc, the point is to study the geometry of the possible emission zone.

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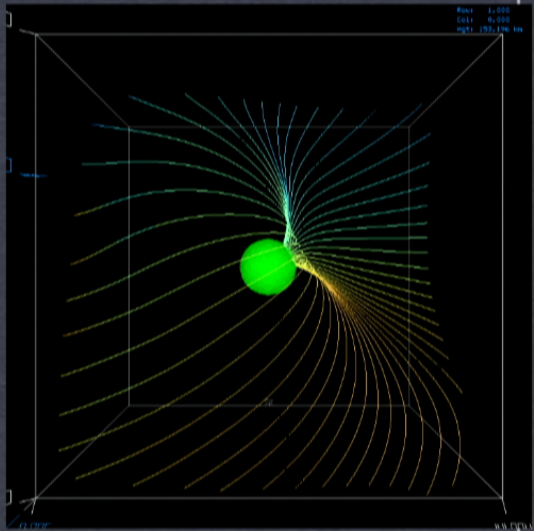

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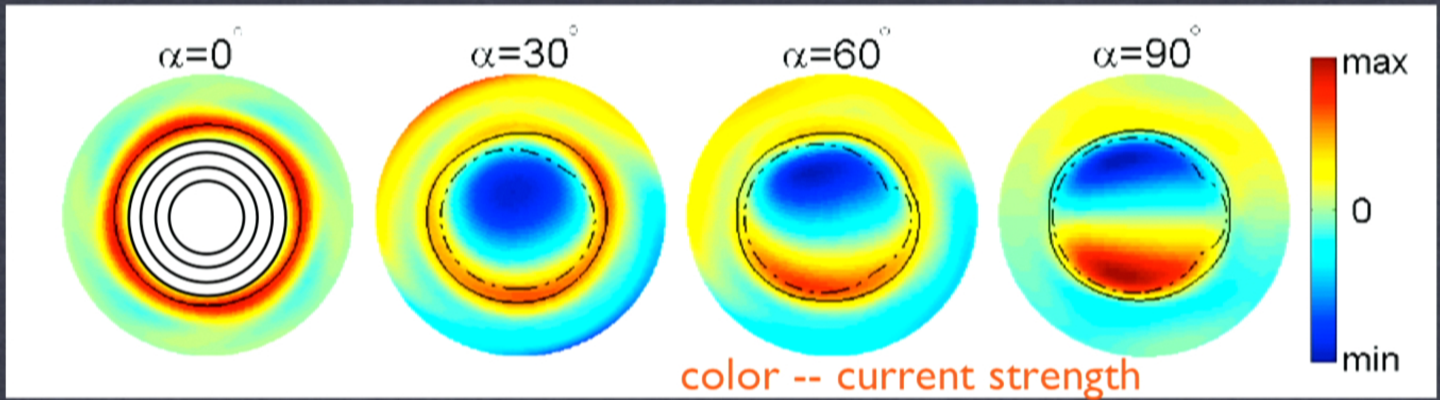

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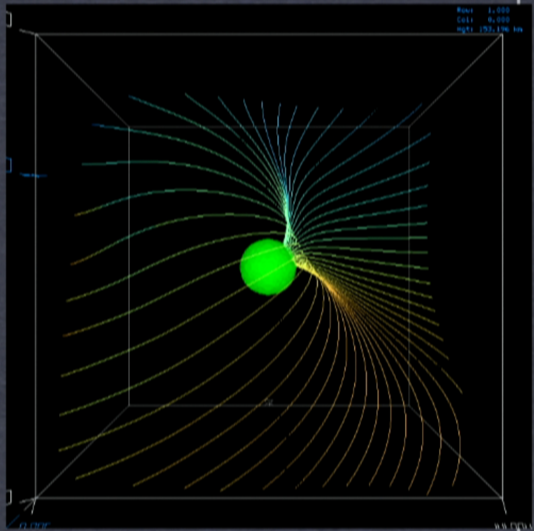
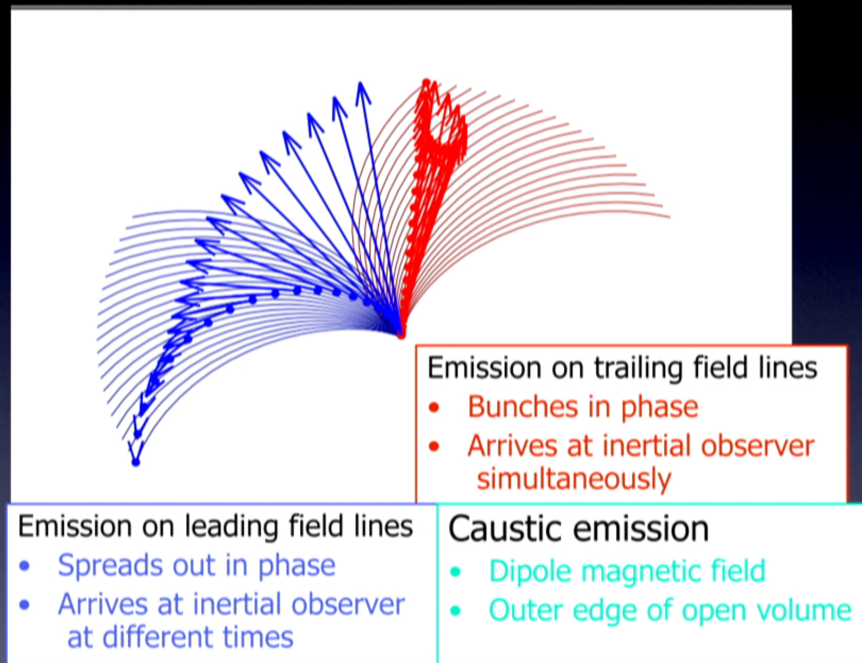


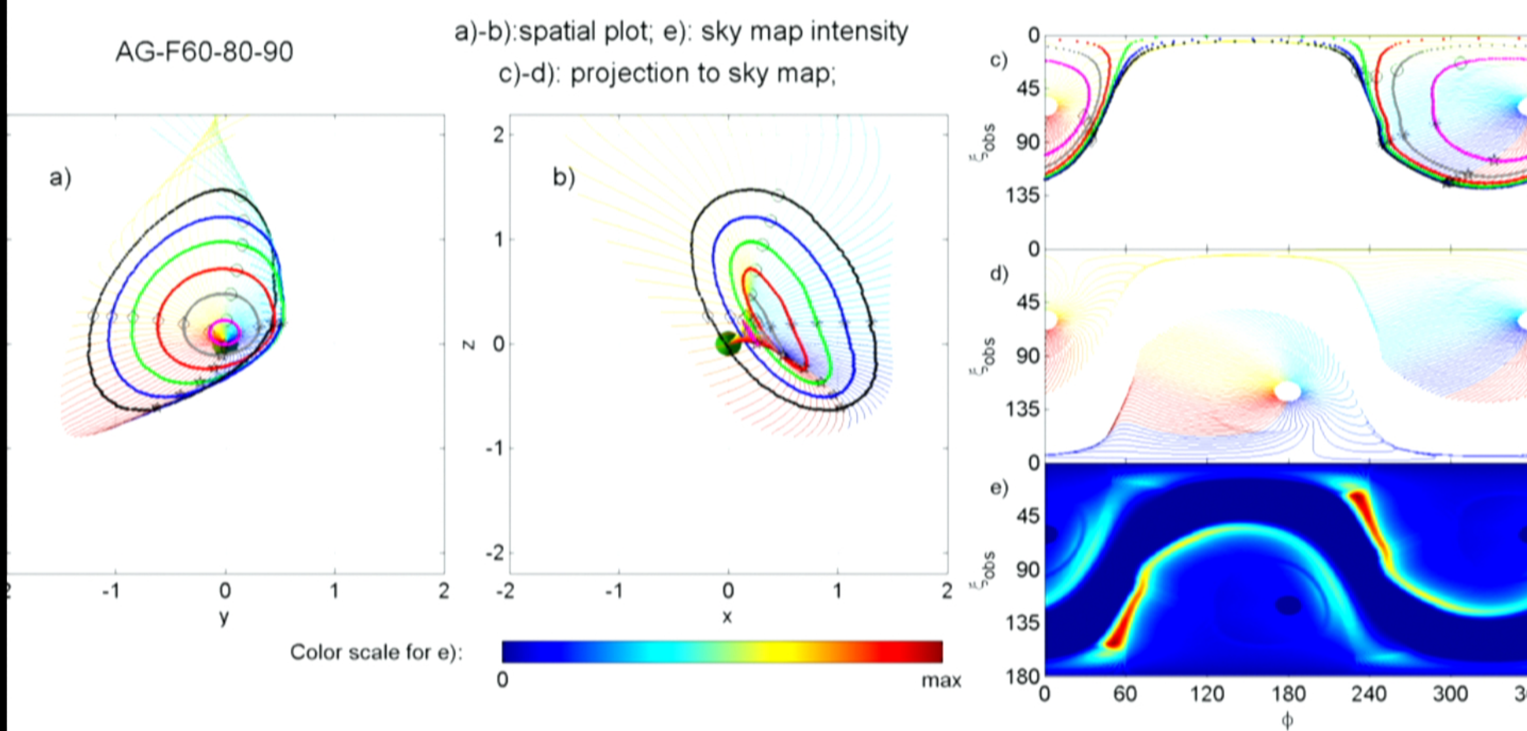
Caustic formation:



Harding 07

Emission from different flux tubes

Bai & A. S. 2010



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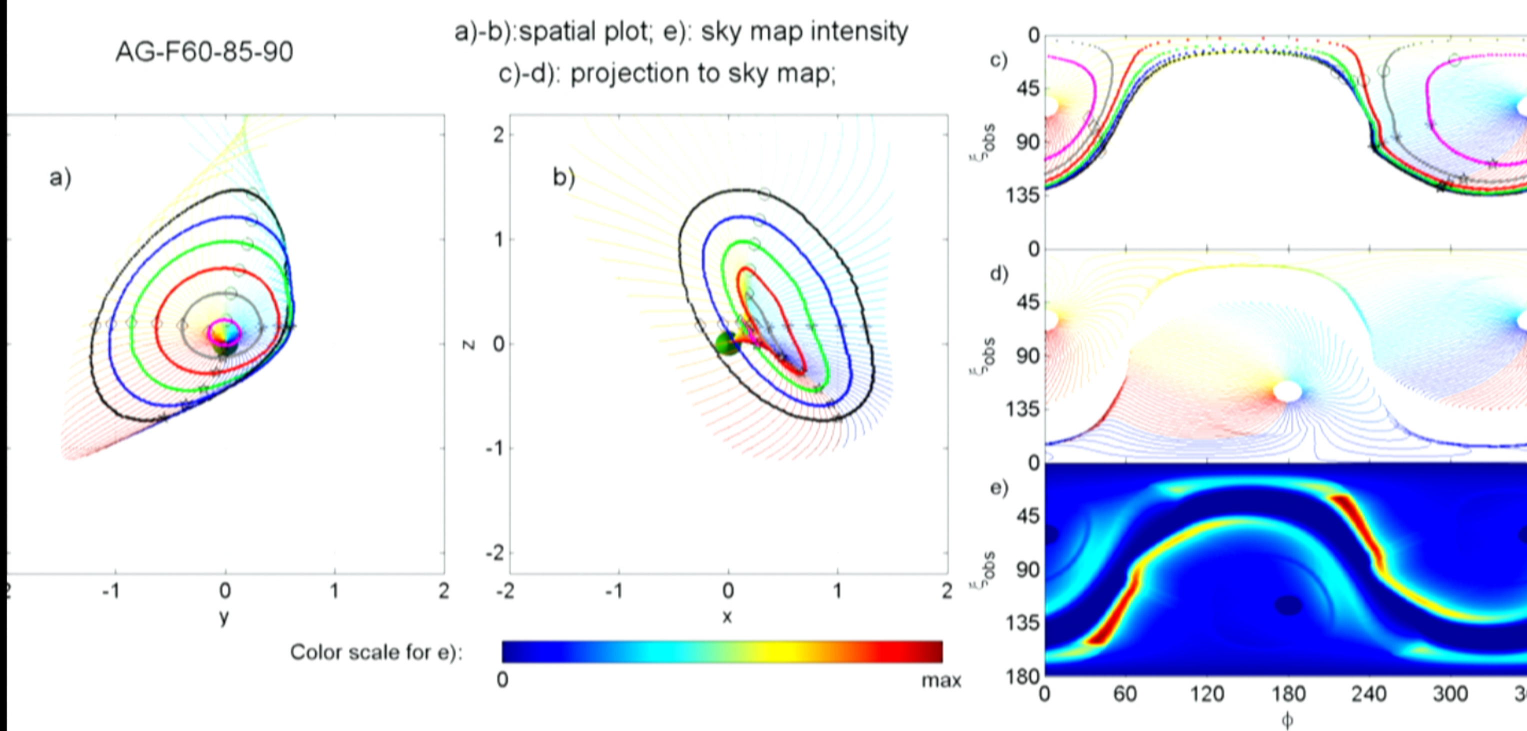

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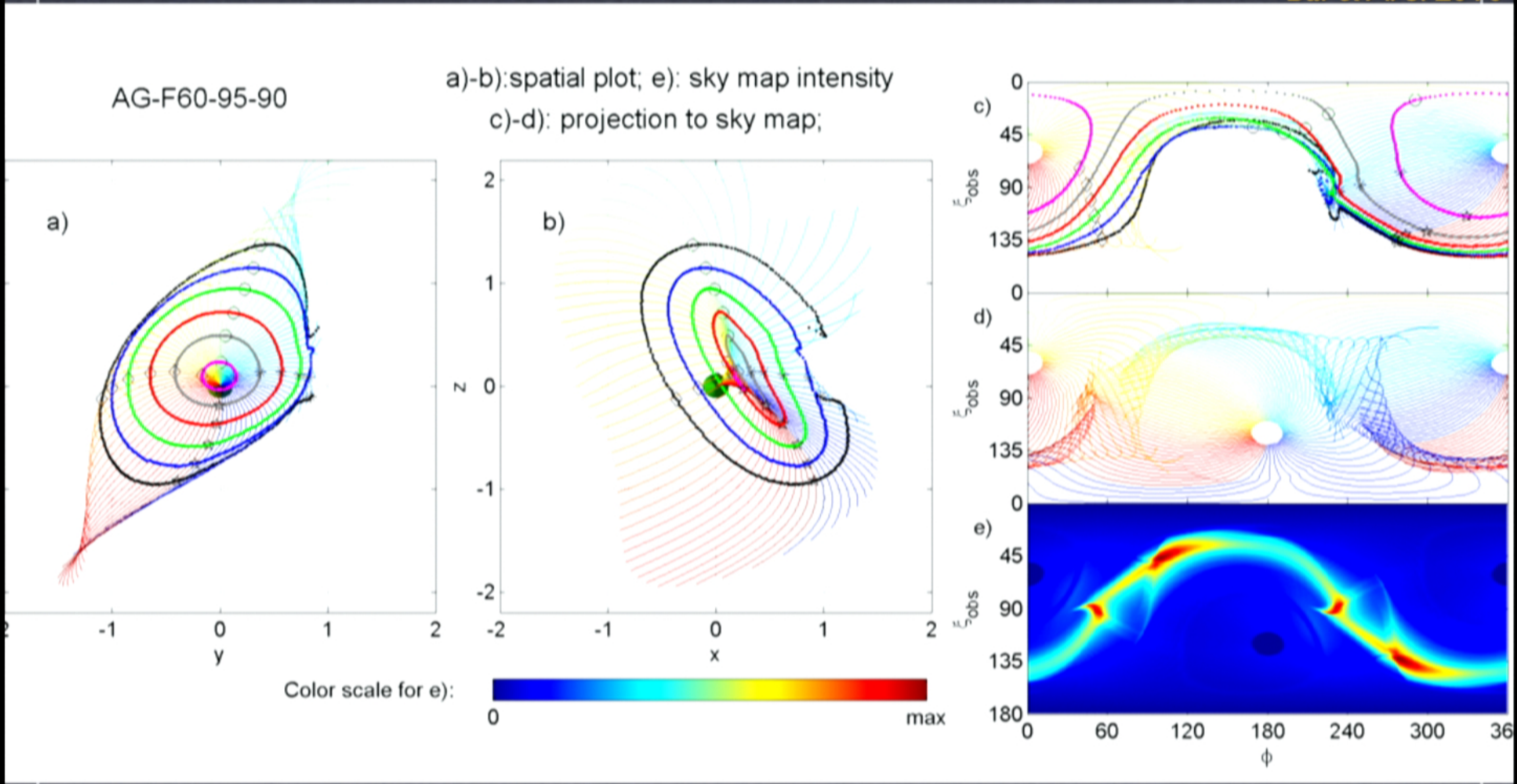

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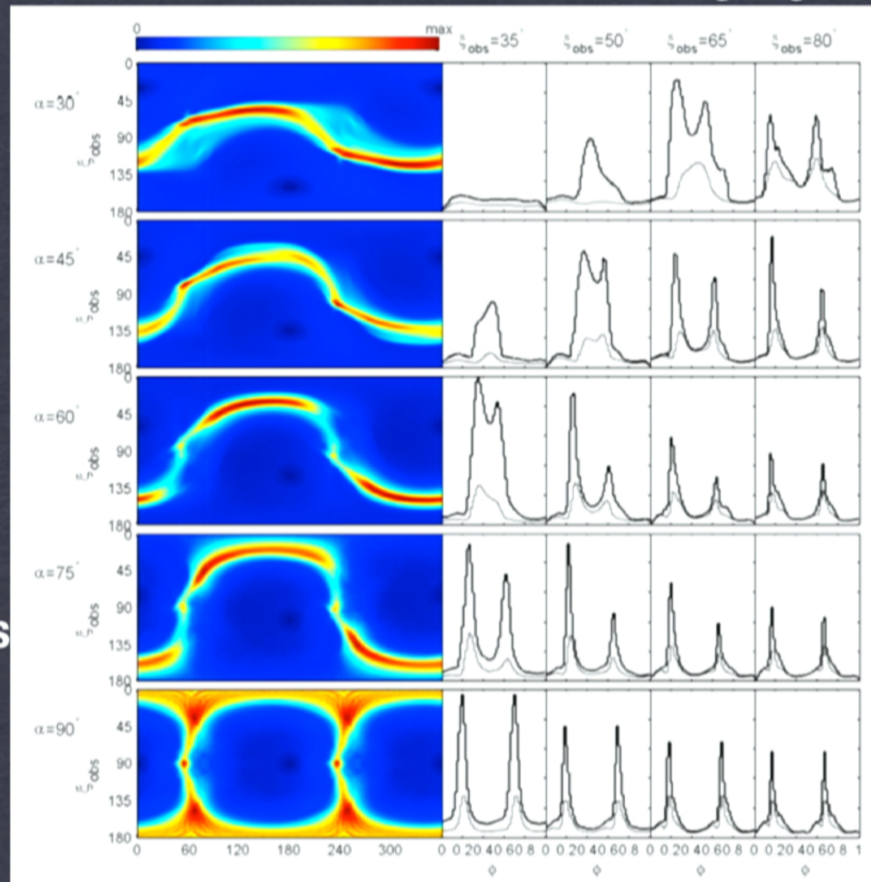
Force-free light curves

Viewing angle

“Separatrix Layer” model is a real contender. It’s not just outer gap vs slot gap anymore!

Inclination angle

Most of the emission in FF model accumulates beyond 0.9 Rlc



Double peak profiles very common.

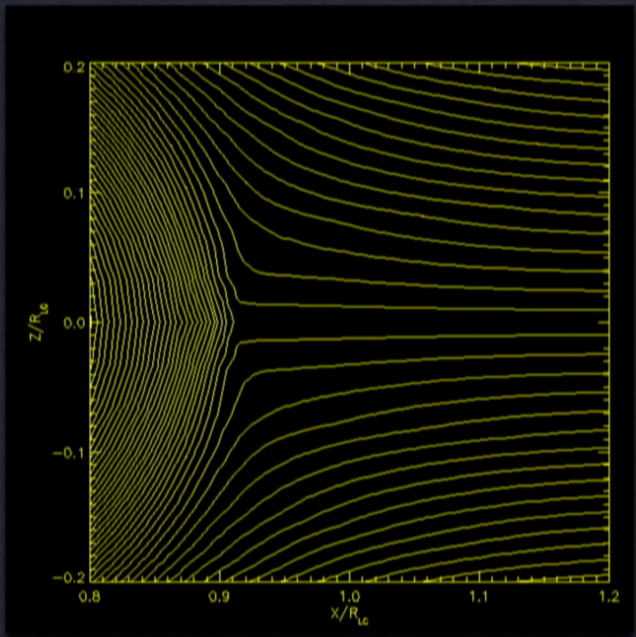
Bai & AS, 2010

Source of emission

- Emission is geometrically associated with the current sheet
- What is the acceleration and radiation mechanism in current sheet?

  Most likely culprit -- relativistic reconnection. This is different from conventional picture of accelerating gaps starved of plasma and curvature emission

- Boosted synchrotron from heated plasma can work



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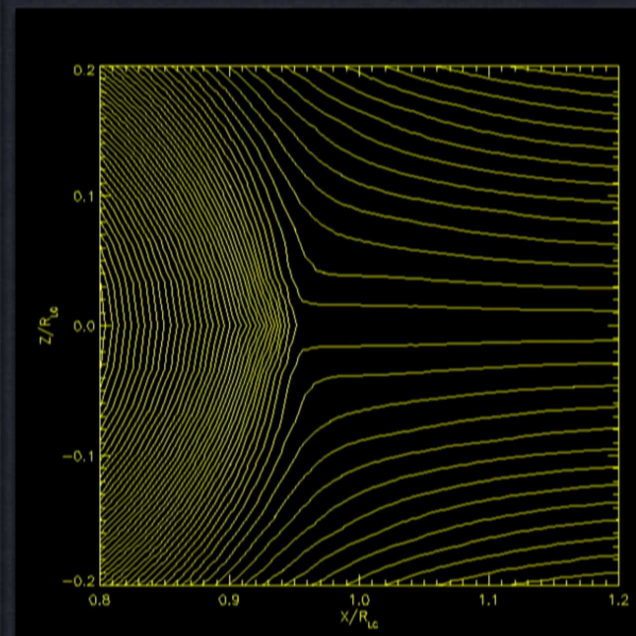

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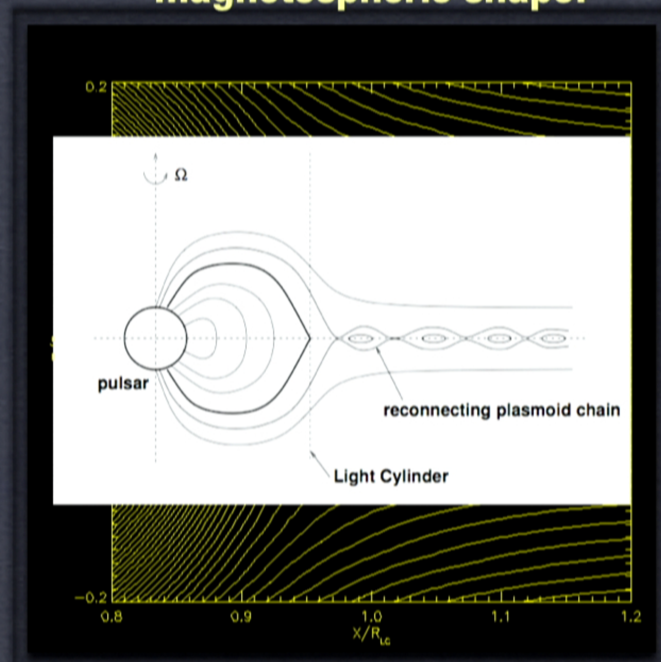

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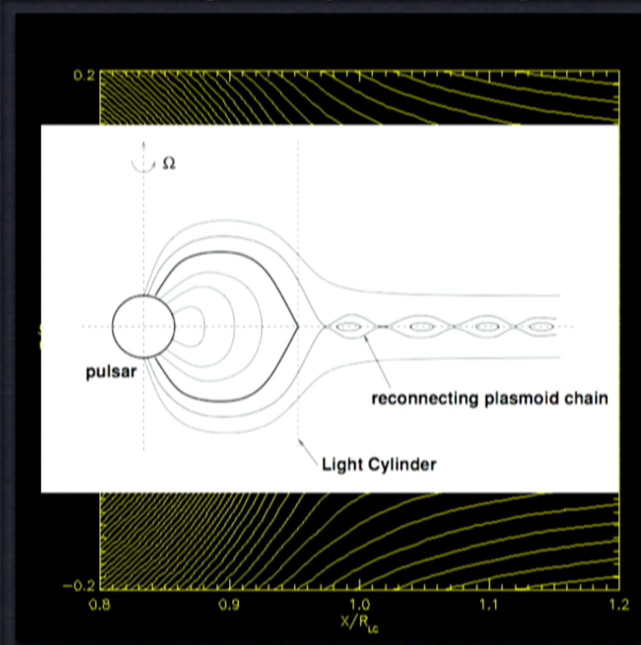

Conclusions

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- Geometrically these models are being contrasted with gamma-ray observations (Separatrix Layer vs Gaps).
- More realistic models with 3D RMHD, cascade physics and full PIC are advancing -- expect cool results in the next few years. Benefit a lot from Moore's law.
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