Particle acceleration and γ-ray emission from pulsars - towards the self-consistent theory

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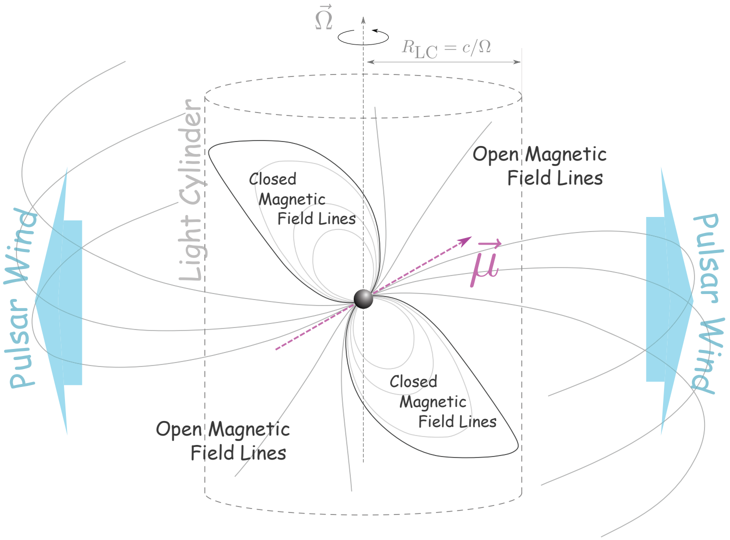
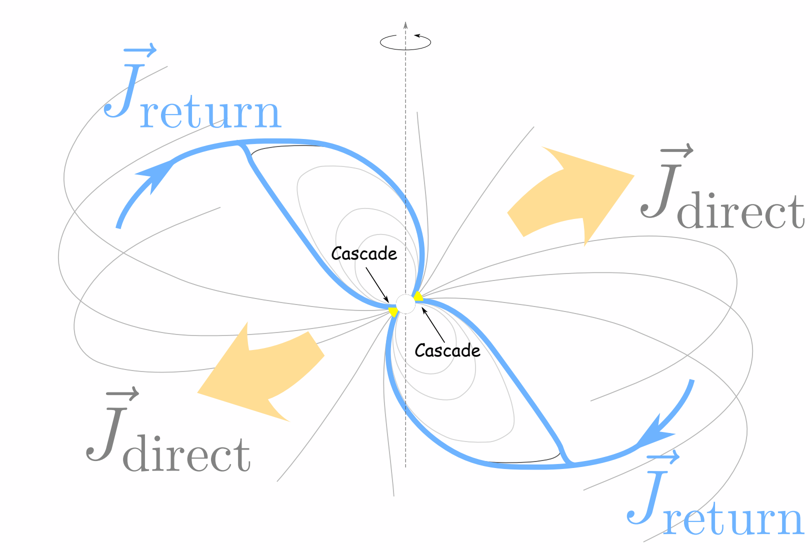
Pulsar Magnetosphere: Large scale view

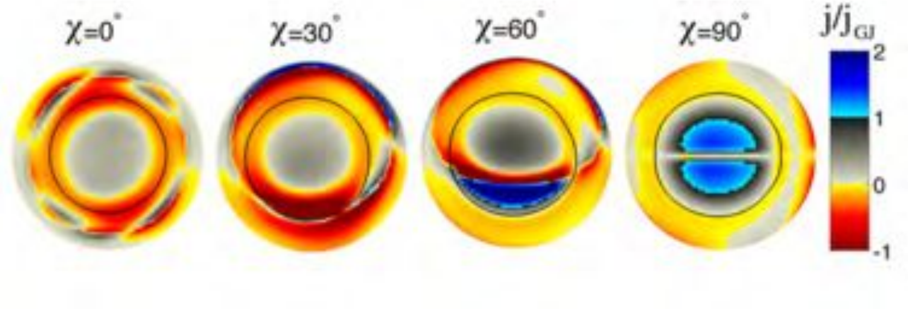


Pulsar Magnetosphere: The global circuit



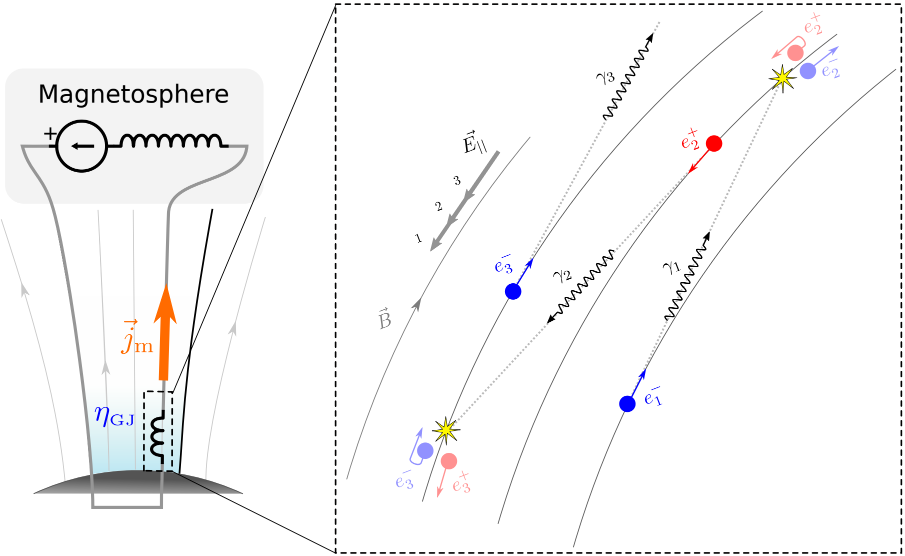
Current density in the polar cap

current density does not match $j \neq j_{\mathrm{GJ}} \equiv \eta_{\mathrm{GJ}} c$



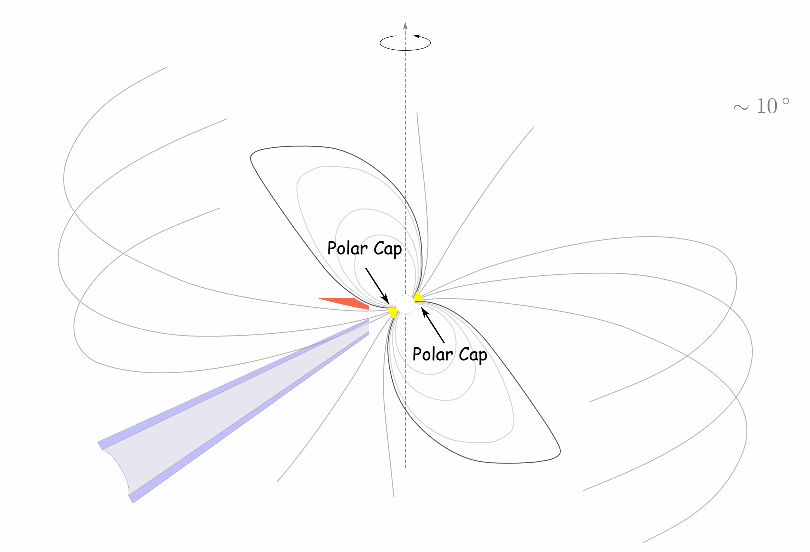
[thanks to Xue-Ning Bai (Bai & Spitkovsky 2010)]

Physical Model: Plasma Flow in an Electric Circuit



Pulsar Magnetosphere: Emission regions

Why is there particle acceleration in the outer magnetosphere?



Boundary Conditions: Models for NS surface

- **[RS]**
  particles **cannot** leave NS surface
  R*uderman &* ***S****utherland (1975) model*

  self-consistent model: Timokhin 2009, 2010

- **[SCLF]**
  particles **freely** leave NS surface – **S**pace **C**harge **L**imited **F**low
  Arons & Scharlemann (1979) model
  (also Muslimov & Tsygan 1992, Harding & Muslimov 1998, and others)

  self-consistent model: Timokhin & Arons 2012

Numerical Model: Modeling from first principles

Numerical Code:

Particle acceleration $\leftrightarrow$ Electric field — **Particle-In-Cell**

Particles $\rightarrow$ Photons $\rightarrow$ Particles(Pairs) — **Monte Carlo**

Physical ingredients:

- 1D Electrodynamics

$$\frac{\partial E_\parallel}{\partial t} = -4\pi(j - j_{\mathrm{m}})$$

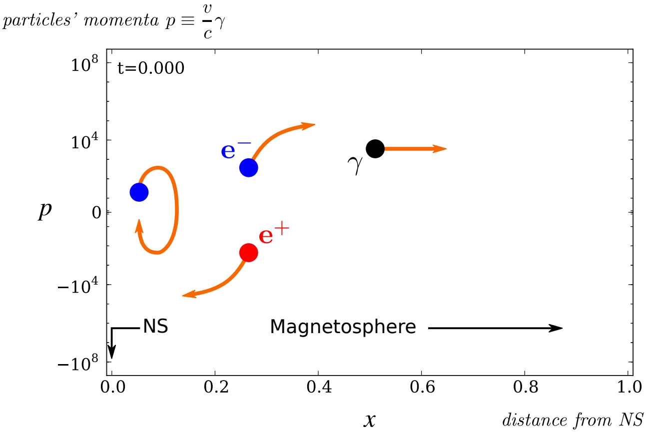
starting from

$$\frac{\partial E_\parallel}{\partial x} = 4\pi(\eta - \eta_{\mathrm{GJ}})$$

- γ-ray production: curvature radiation
- pair creation: single photon absorption in magnetic field

RS: No particles supplied by the NS $j = j_{GJ}$

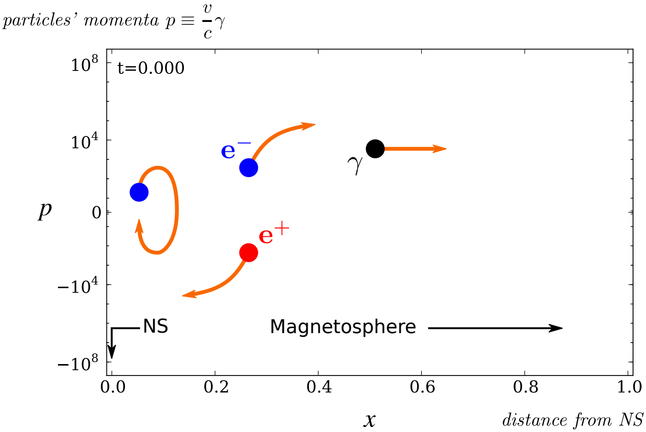
Limit cycle: series of discharges



• electrons • positrons • γ-rays

RS: No particles supplied by the NS $j = j_{GJ}$

Single discharge



• electrons • positrons • γ-rays

SCLF: Low energetic flow $0 < j/j_{\mathrm{GJ}} < 1$

Formation of the low energetic flow

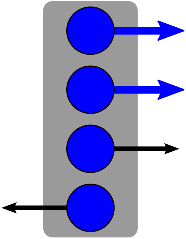
SCLF_xp_jm05_OF_development.mp4

Dashed red line – oscillating solution in one-fluid approximation

Mestel & Pryce (1985), Shibata (1997), Beloborodov (2008)

SCLF: Low energetic flow $0 < j/j_{GJ} < 1$

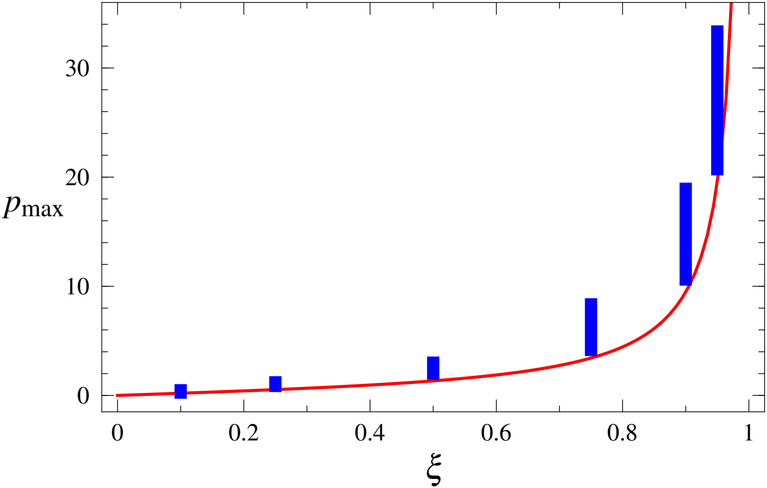
Current and charge density adjustment: beam and cloud



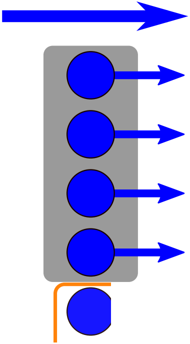
SCLF_xp_jm05_fragment.mp4

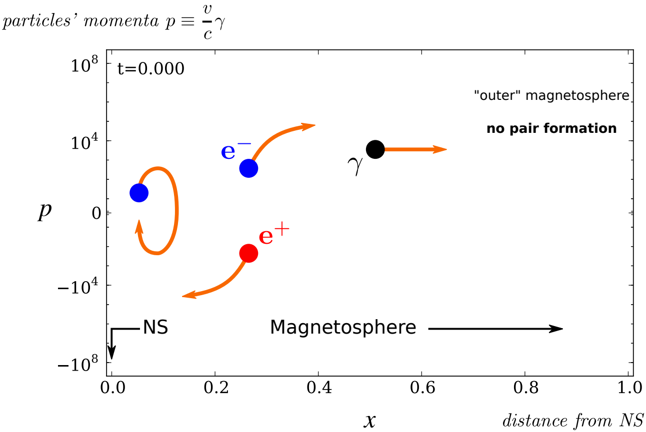
SCLF: Low energetic flow $0 < j/j_{GJ} < 1$

Maximum particle momentum as a function of $\xi \equiv j/j_{GJ}$



SCLF: Discharges in super-GJ flow $j/j_{GJ} > 1$

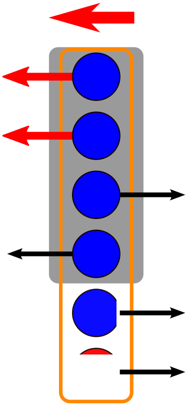


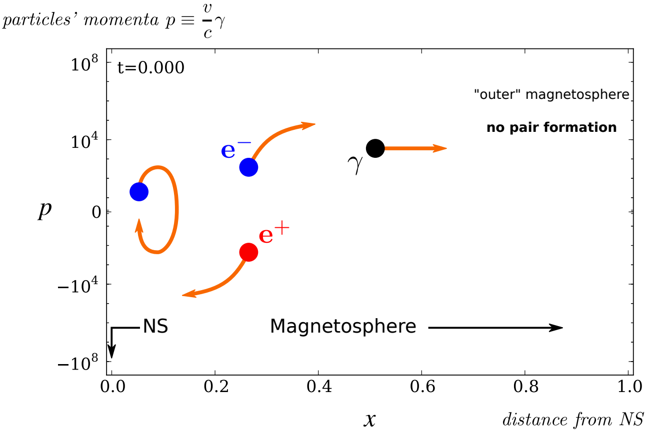


• electrons • positrons • γ-rays • protons

Discharges in the return current $\quad j/j_{GJ} < 0$

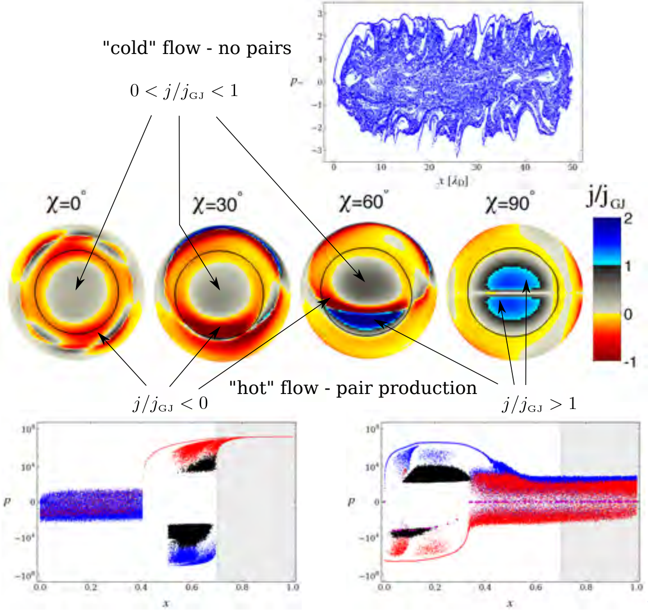
The same for both RS and SCLF





• electrons • positrons • γ-rays

Particle acceleration in SCLF regime



Particles' momenta:
p~[0,10]

electrons

Polar cap currents

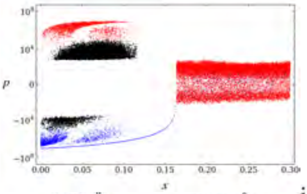
Particles' momenta:
p~[0,10^7]

electrons
positrons
photons

Particle acceleration in RS regime

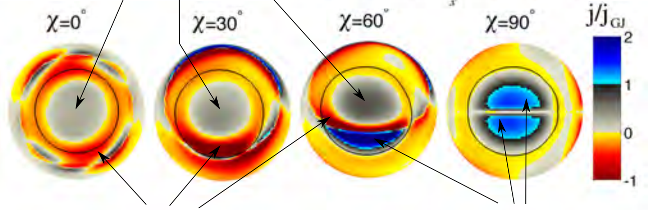
"hot" flow everywhere,
pair production:

near NS $0 < j/j_{\rm GJ} < 1$



Particles' momenta:
p~[0,10^7]

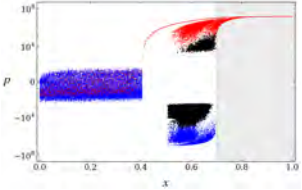
electrons
positrons
photons

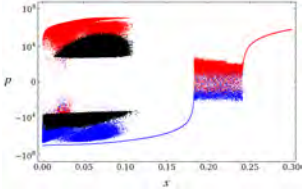


Polar cap currents

far from NS $j/j_{\rm GJ} < 0$

near NS $j/j_{\rm GJ} > 1$





Particles' momenta:
p~[0,10^7]

electrons
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Conclusions

- Current density determines the plasma flow regime
- Cascades are non-stationary. ALWAYS.
- All flow regimes look different.
- Return current regions should be particle accelerating regions in the outer magnetosphere: γ-ray pulsars (?)

More on pulsars…

Posters on global magnetosphere structure and its observational fingerprints

- Alice Harding – poster **2.10**
- Constantinos Kalapotharakos – poster **2.9**

Acknowledgments

3-D model of the pulsar current sheet structure was made by

- Steven J. Kenyon (GSFC)
- Devin J. Hahne (GSFC)
- Constantinos Kalapotharakos (UMD/GSFC)
  (if you want to look at the model come to see his poster)