Origin of pulsar radio emission

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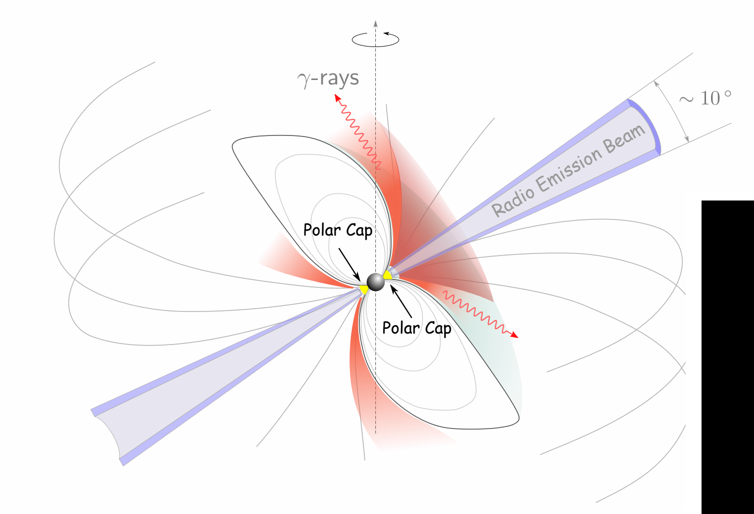
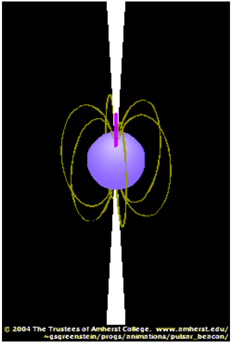
Pulsar: rapidly rotating magnet surrounded by plasma

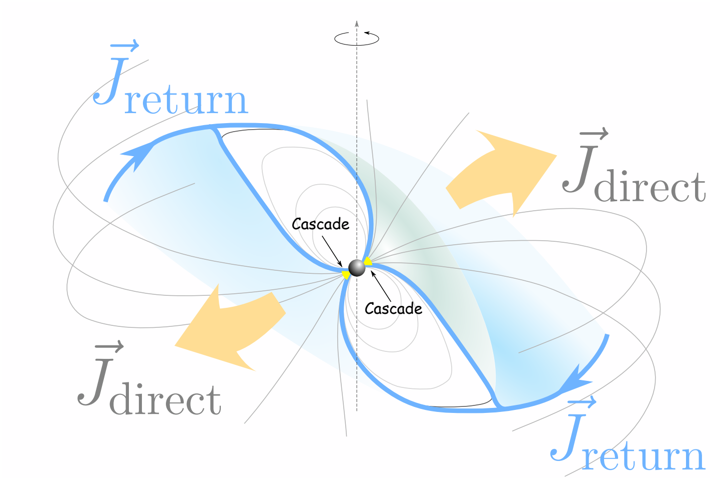
“Electric lighthouse”





Magnetosphere is supported by electrical currents

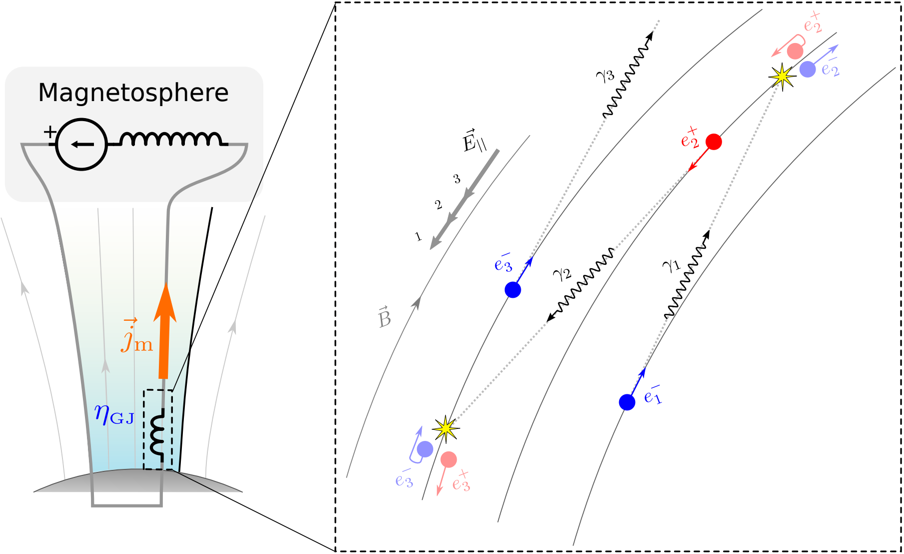
Electrical generator (NS) + Wires (plasma)



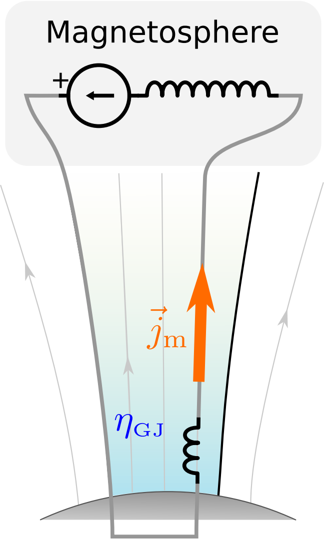
The magnetosphere is charged
characteristic charge density – “Goldrech-Julian” density $\eta_{\rm GJ}$.

Plasma creation in the polar cap

Particle acceleration is regulated by pair production



Polar Cap Electrodynamics



- Rotation of the NS

$$\nabla \cdot \boldsymbol{E} = 4\pi(\eta - \eta_{\rm GJ})$$

- Twist of magnetic field lines

$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c} j + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t}$$

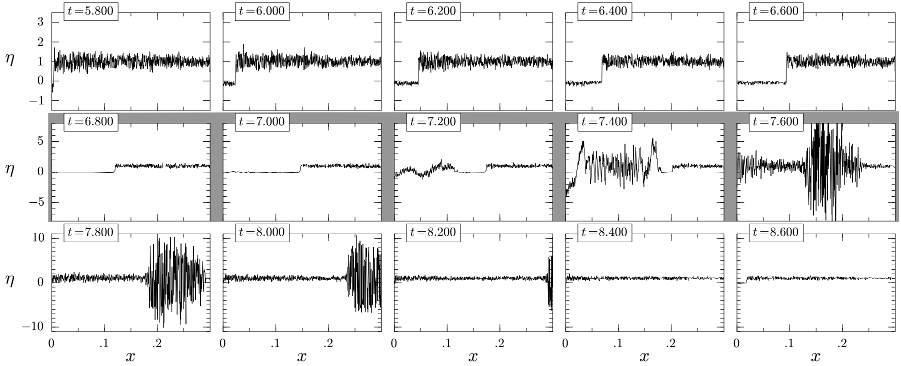
- $\boldsymbol{E} = 0$ if both

$$\eta = \eta_{\rm GJ}$$

$$j = j_{\rm m} \equiv \frac{c \nabla \times \boldsymbol{B}}{4\pi}$$

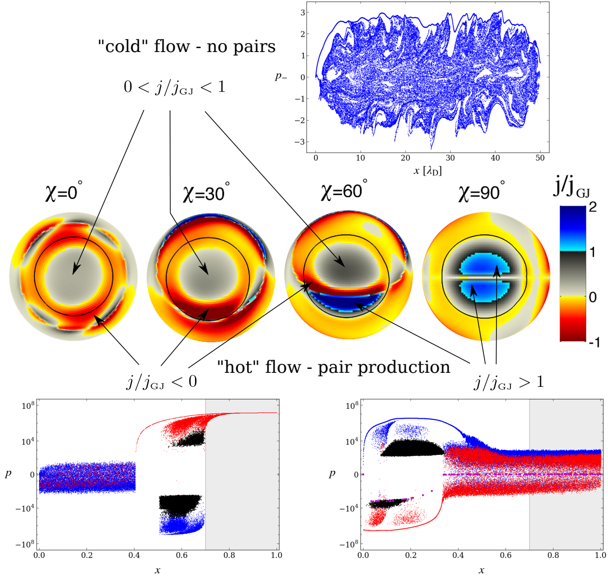
Pair creation is highly non-stationary

Limit cycle: series of discharges



Pair creation is non-uniform across the polar cap

Free particle extraction from the NS surface [AT & Arons'13]



Particles' momenta:
p~[0,10]

electrons

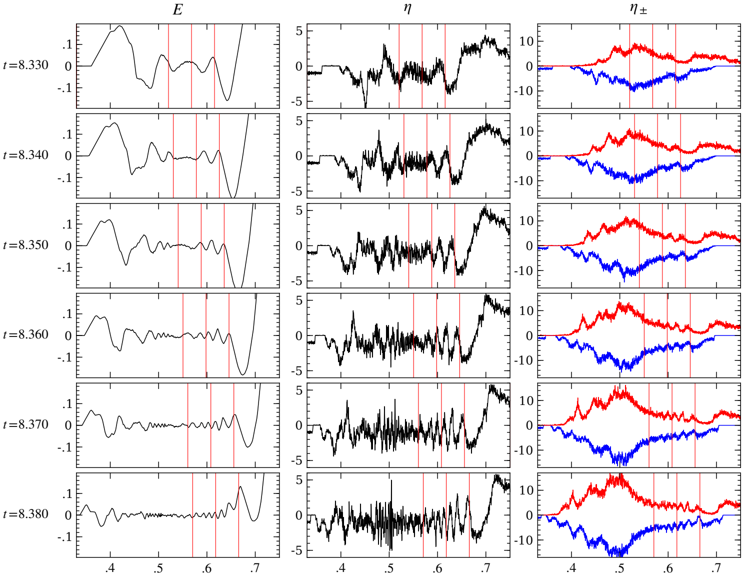
Polar cap currents

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

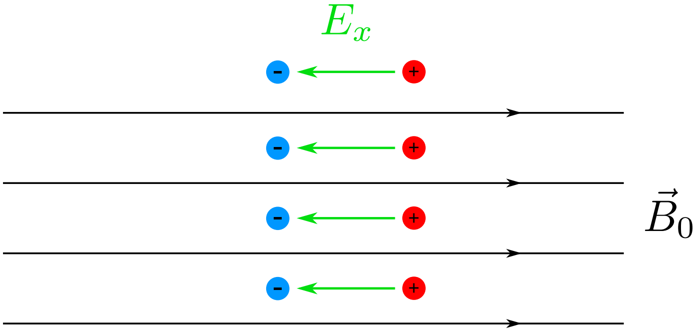
electrons
positrons
photons

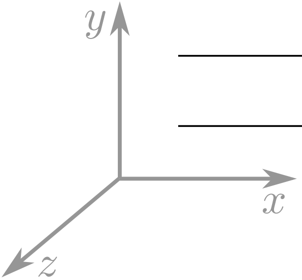
Waves during discharge: Coherent plasma motion (!)

In 1D only electrostatic Langmuir waves exist [AT & Arons '13]



Pair formation uniform across $\boldsymbol{B}_0 \longrightarrow$ no EM mode



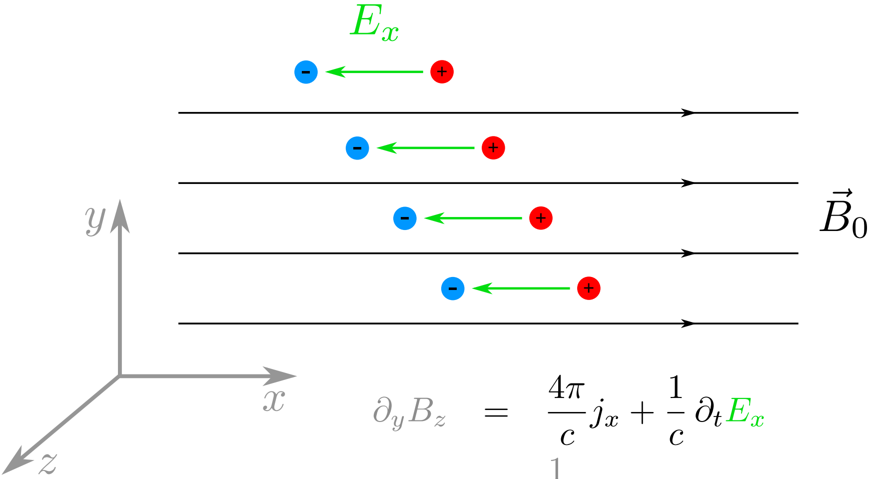


$$\partial_y B_z = \frac{4\pi}{c} j_x + \frac{1}{c}\,\partial_t E_x$$

$$-\partial_x B_z = \frac{1}{c}\,\partial_t E_y$$

$$\partial_x E_y - \partial_y E_x = -\frac{1}{c}\,\partial_t B_z$$

Inclined pair formation front: non-zero $\nabla \times \boldsymbol{E}$



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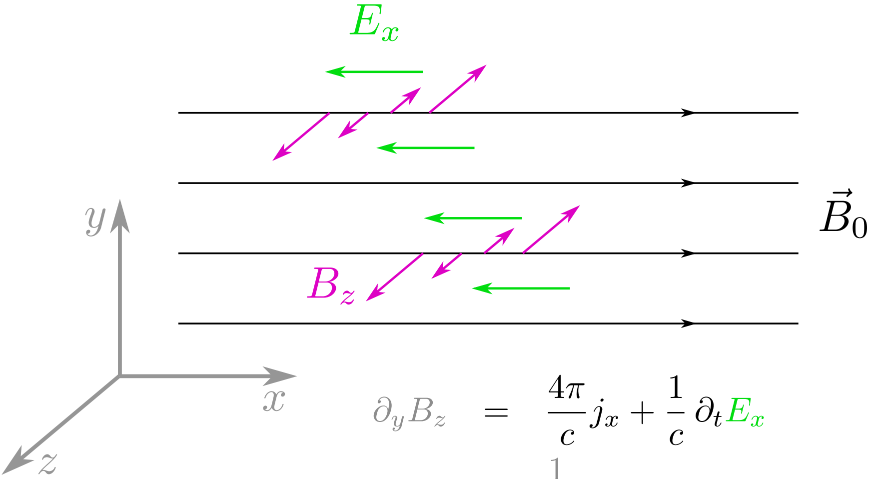
Inclined pair formation front: $\nabla \times \boldsymbol{E} \longrightarrow B_z$



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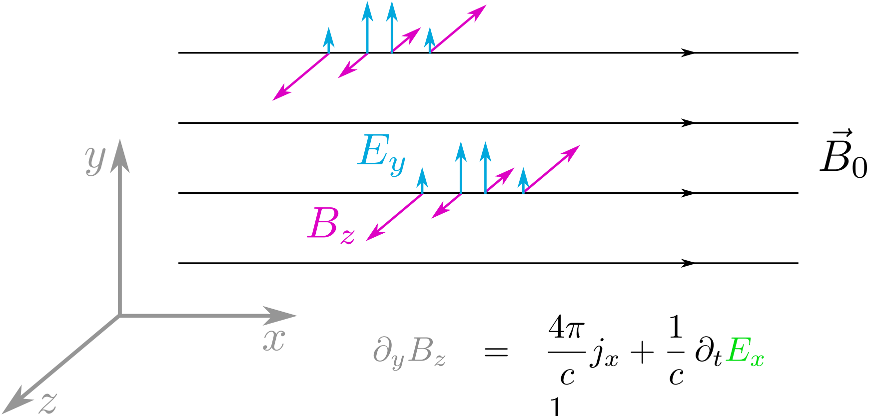
$$-\partial_x B_z = \frac{1}{c}\,\partial_t E_y$$

$$\partial_x E_y - \partial_y E_x = -\frac{1}{c}\,\partial_t B_z$$

Non-uniform B_z in x direction: $\nabla \times \boldsymbol{B} \longrightarrow E_y$



$$\partial_y B_z = \frac{4\pi}{c} j_x + \frac{1}{c}\,\partial_t E_x$$

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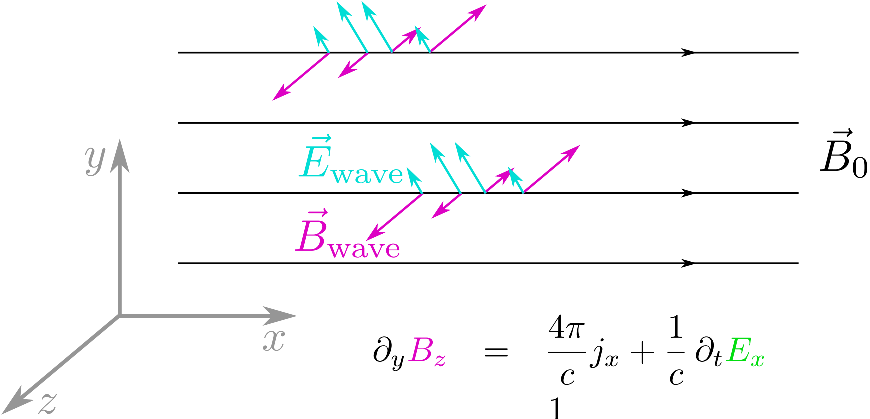
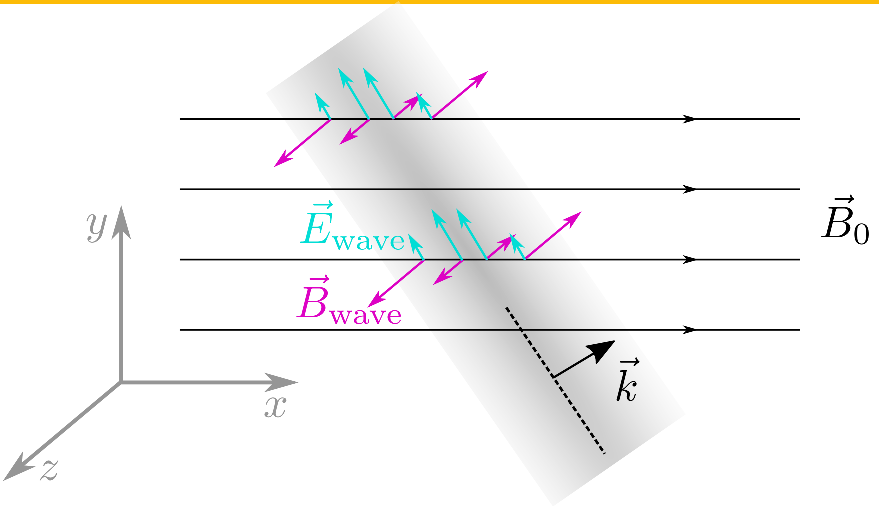
Electromagnetic mode: $\boldsymbol{B}_{\rm wave} \perp \boldsymbol{E}_{\rm wave}$

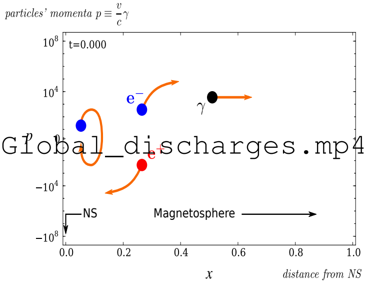


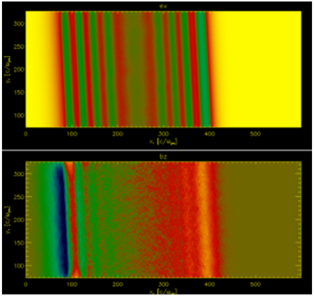
$$
\begin{aligned}
\partial_y B_z &= \frac{4\pi}{c} j_x + \frac{1}{c}\,\partial_t E_x \\
-\partial_x B_z &= \frac{1}{c}\,\partial_t E_y \\
\partial_x E_y - \partial_y E_x &= -\frac{1}{c}\,\partial_t B_z
\end{aligned}
$$

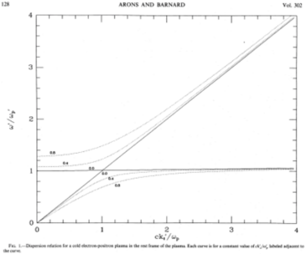
Ordinary mode: $\boldsymbol{E}$ lies in the plane $(\boldsymbol{k}\ \boldsymbol{B}_0)$



2D PIC simulation of inclined discharge: it works!







- Oblique discharge directly excites a superluminal O-mode with non-zero $k_\perp$, which has EM component.
- As plasma density drops, these waves should become vacuum EM.
- Super-luminal O-mode can not be a result of a streaming instability.

This mechanism generates the right kind of waves!

128 ARONS AND BARNARD Vol. 302

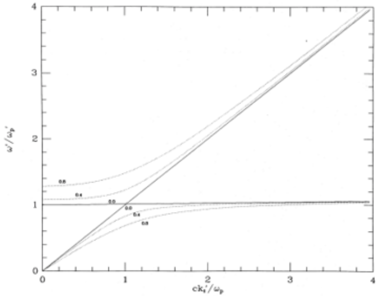
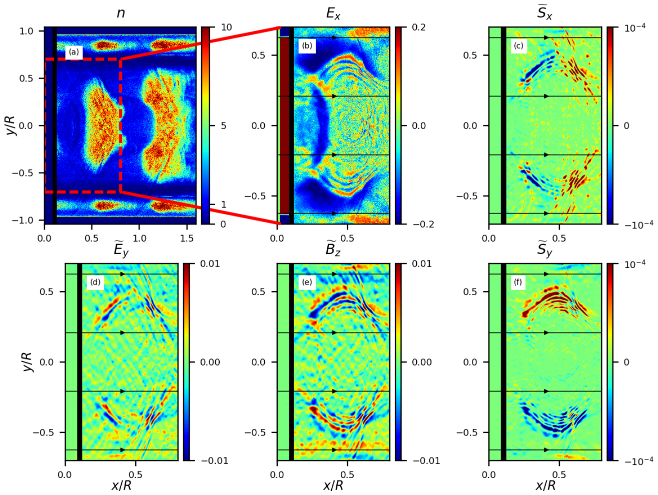


FIG. 1.—Dispersion relation for a cold electron-positron plasma in the rest frame of the plasma. Each curve is for a constant value of $ck_\perp'/\omega_p'$ labeled adjacent to the curve.

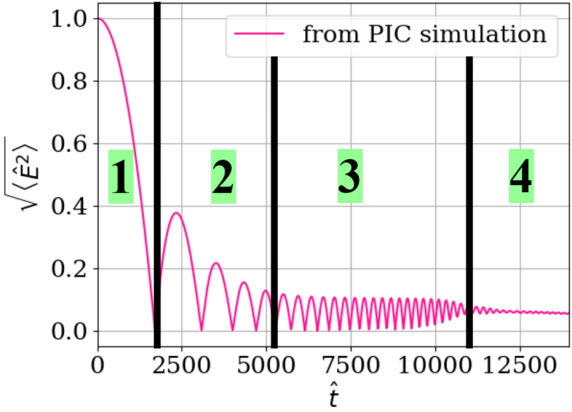
- Oblique discharge directly excites a superluminal O-mode with non-zero $k_\perp$, which has EM component.
- As plasma density drops, these waves should become vacuum EM.

Toy 2D PIC model of polar cap discharges

Pair formation threshold varies across parallel magnetic field lines



[Philippov, AT, Spitkovsky '20]



1. initial screening
2. non-linear waves exponential damping
3. non-linear waves “frozen phase”
4. **linear damping**

[Tolman, Philippov, AT ’22]

Conclusions

- Pulsars live when they produce $e^{\pm}$ pairs in polar caps.
- Pair formation is non-stationary and non-uniform.

- Radio emission can be produced directly by the discharges
- The mechanism does not require any special conditions (besides those already existing in polar caps)
- It generates the right kind of waves
- The waves seem to survive.