Formation of Relativistic Outflows

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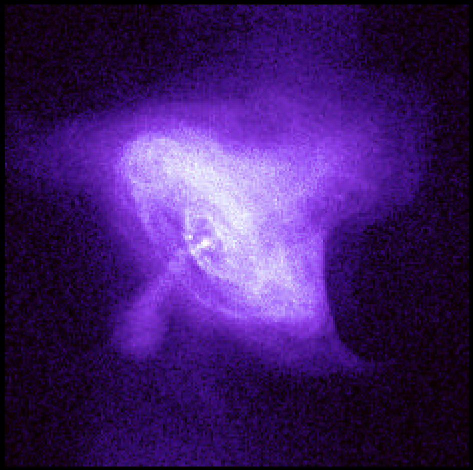
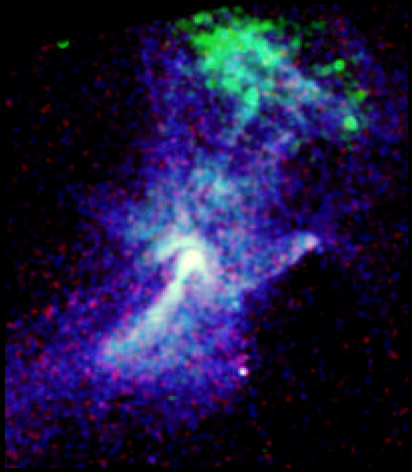
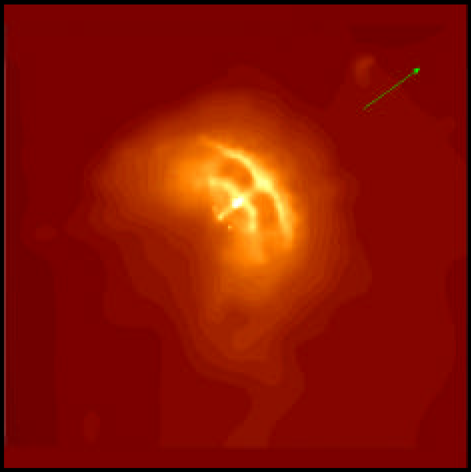


Weisskopf et al 00

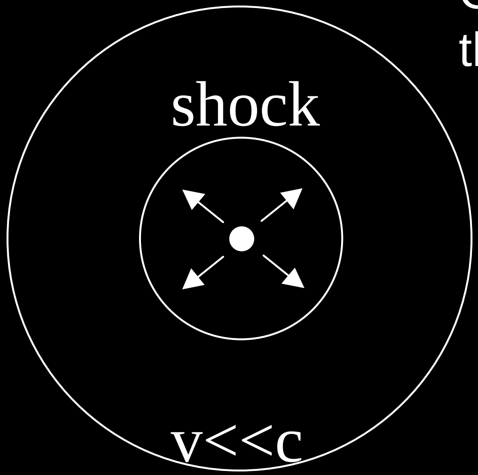


Gaensler et al 02



Pavlov et al 01

Relativistic outflows are ubiquitous : AGN jets, pulsar winds, and GRBs. Chandra's unique view of pulsar wind nebulae provides the closest examples of magnetized rotators at work.



Properties of pulsar winds:

Highly relativistic ($\gamma \sim 10^6$)

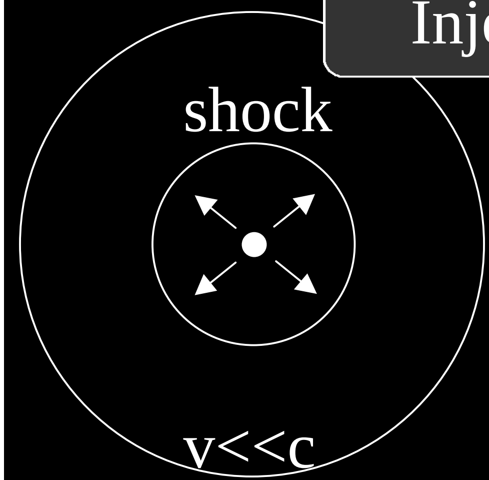
Kinetic energy dominated at the nebula ($\sigma \sim 10^{-3}$)

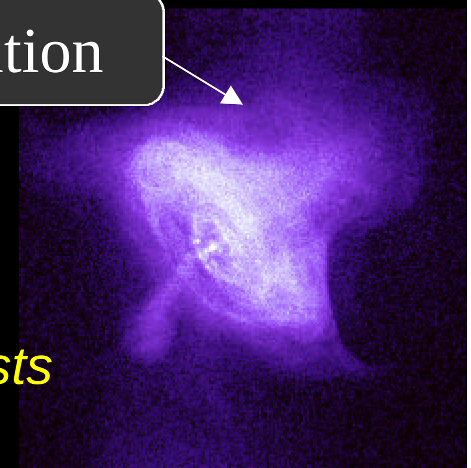
Pole-equator asymmetry and collimation

How do they do this?

Theoretical view of pulsar magnetospheres

Injection → Transport → Deposition





No self-consistent theory of injection exists

Range of partial models (convictions/religious beliefs)

Current closure problem

1. Polar cap electrodynamics + pair production do the trick

   (but … Poynting dominated outflow -- high σ)

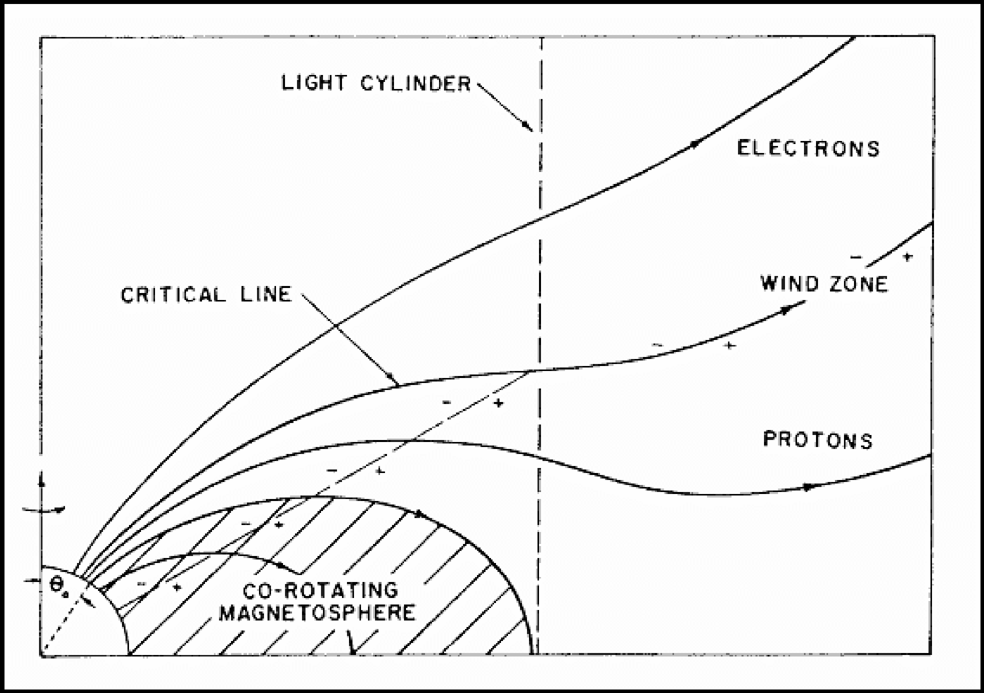
2. Acceleration and collimation should happen far from the pulsar due to breakdown of ideal MHD.

   (but … no detailed model ever succeeded)

3. Pulsar outflows should not exist at all.

   (but … what are we seeing then?!!!)

Standard picture of the pulsar magnetosphere



Holloway's (73) paradox:

- All of the closed zone cannot be filled from the star with the right charge
- Pair creation is unlikely in this region as well.
- Null surface prone to gap formation -- current closure?

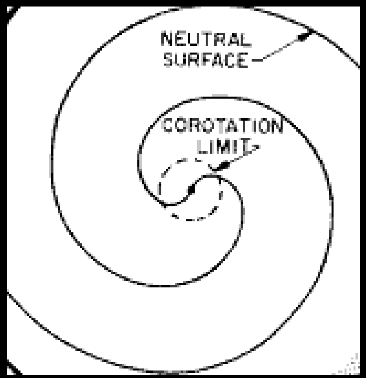
Features of GJ picture:

- Corotating magnetosphere

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

$$\frac{1}{4p}\nabla\cdot\vec{E} = r_{GJ} = -\frac{\vec{\Omega}\cdot\vec{B}}{2pc}$$

- Charge-separated flow
- Field distorted by particle currents
- Energy loss -- Poynting $\vec{B}_f \times \vec{E}_q$ also =current x voltage. No need for obliquity for spindown!



Is Goldreich-Julian picture viable?

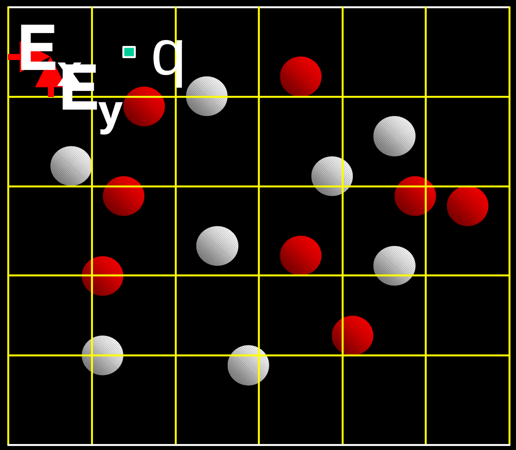
Pulsar magnetospheres after 30+ years

Fundamental unsolved problem:

What happens to a strongly magnetized rotating conducting sphere with no surface work function?

Does it form a magnetosphere and/or a wind? If so, what are its properties?

Strategy: investigate qualitative behavior using numerical simulations.



Particle-in-cell method:

- *Collect currents at the cell centers*
- *Find fields on the mesh (Maxwell's eqs)*
- *Interpolate fields to particles positions*
- *Move particles under Lorentz force*

Can handle vacuum gaps, counterstreaming, space-charge flows

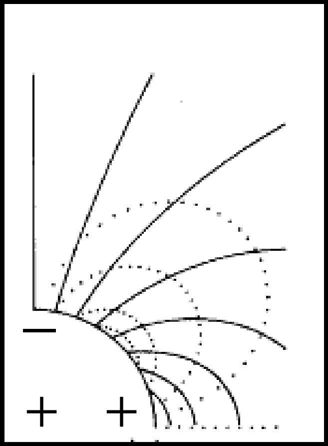
Aligned Rotator: vacuum fields

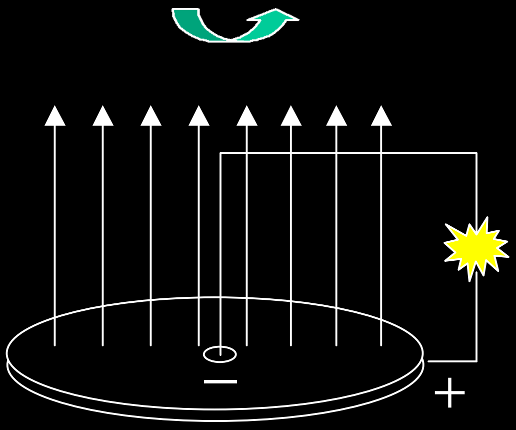
How does plasma know about spin of the star?

Induced quadrupole + monopole

$$E_r = \frac{2}{3} f_0 \frac{a}{r^2} + f_0 \frac{a^3}{r^4}(1 - 3\cos^2 J)$$

$$E_J = -f_0 \frac{a^3}{r^4} \sin 2J \quad f_0 = \Omega B a^2 / c$$





Faraday disk

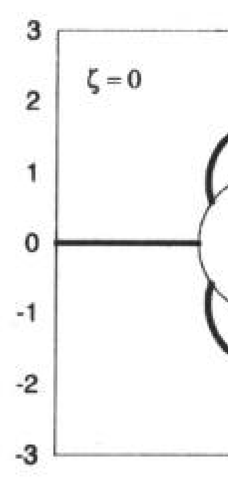
Rotating conductor boundary condition:

not $E_{tangential}$=0, rather $E \cdot B = 0$ inside.

Vacuum field contains central charge and surface charge.

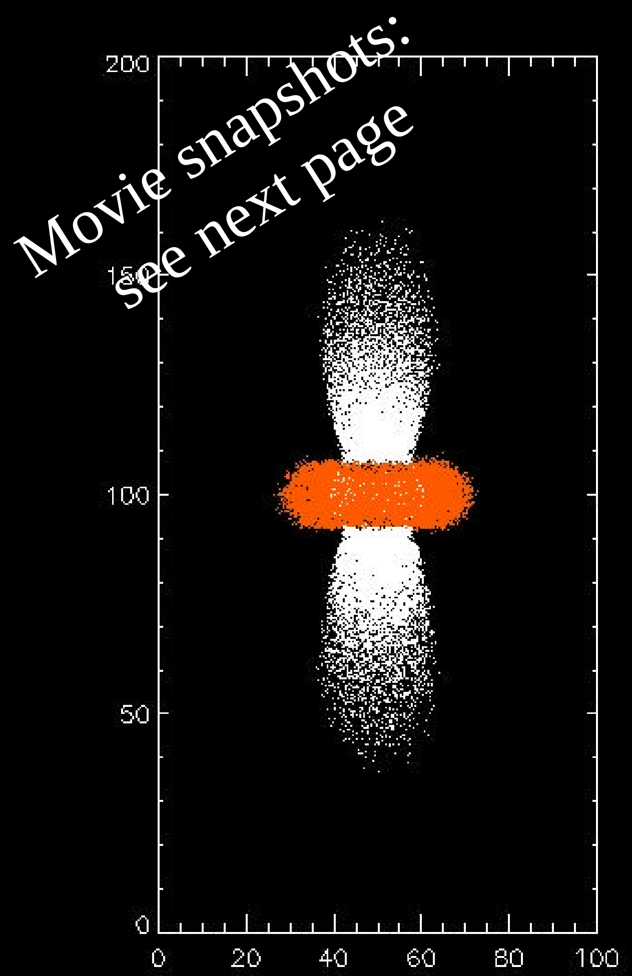
Behavior of charges outside the conductor is governed by the $E \cdot B = 0$ surfaces.

Trapping regions

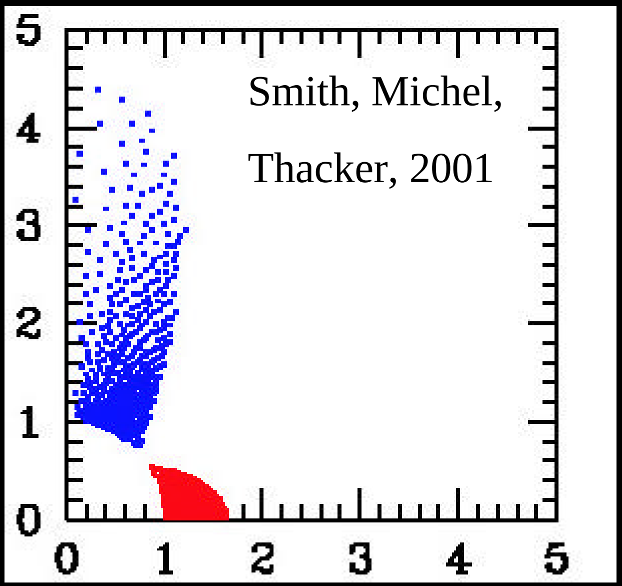


Michel, Li, 99

Aligned Rotator: electrospheres



Surface charges allowed to fly off the surface

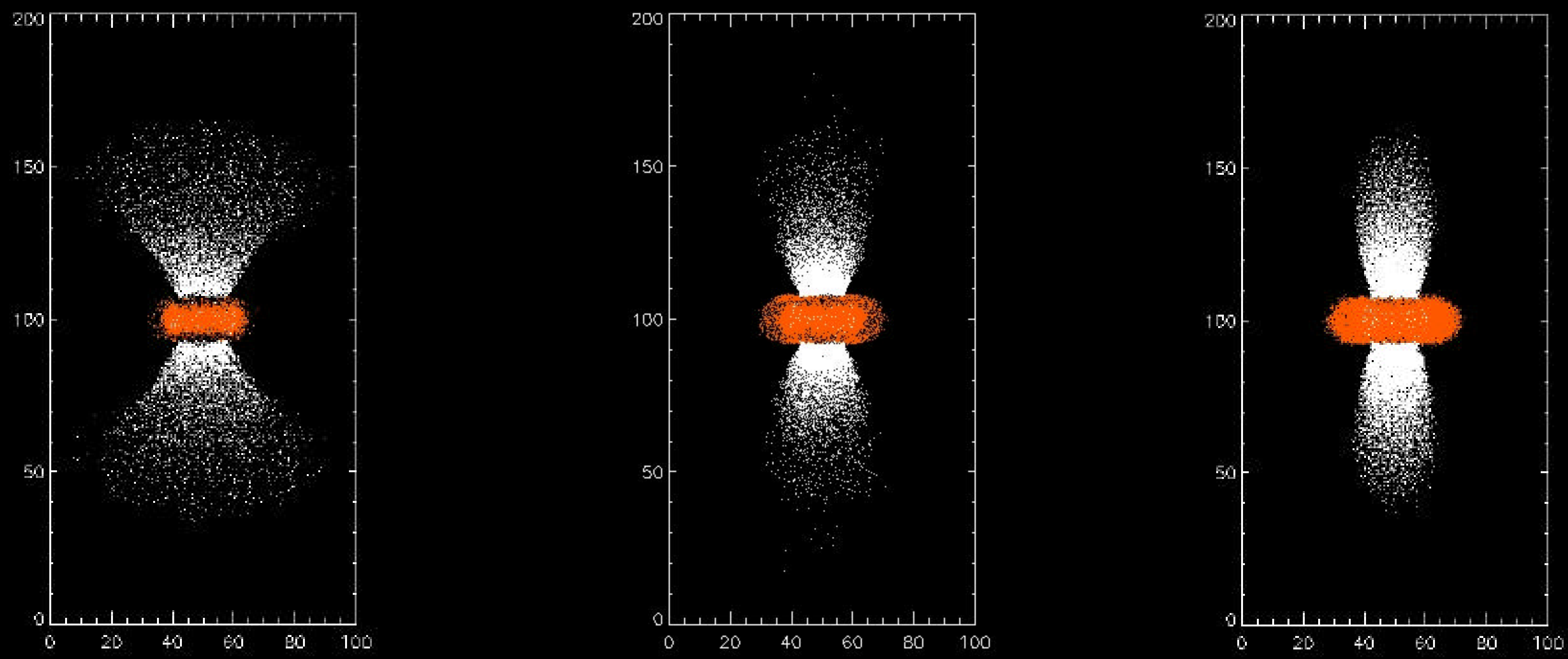


- Non-neutral configuration: dome+disk solution
- Plasma-filled $E \cdot B = 0$ surface, shearing flow.
- Vacuum gaps. Similar to Michel et al '85,'01

Simulation comes to equilibrium where no more charge is emitted. No net wind!

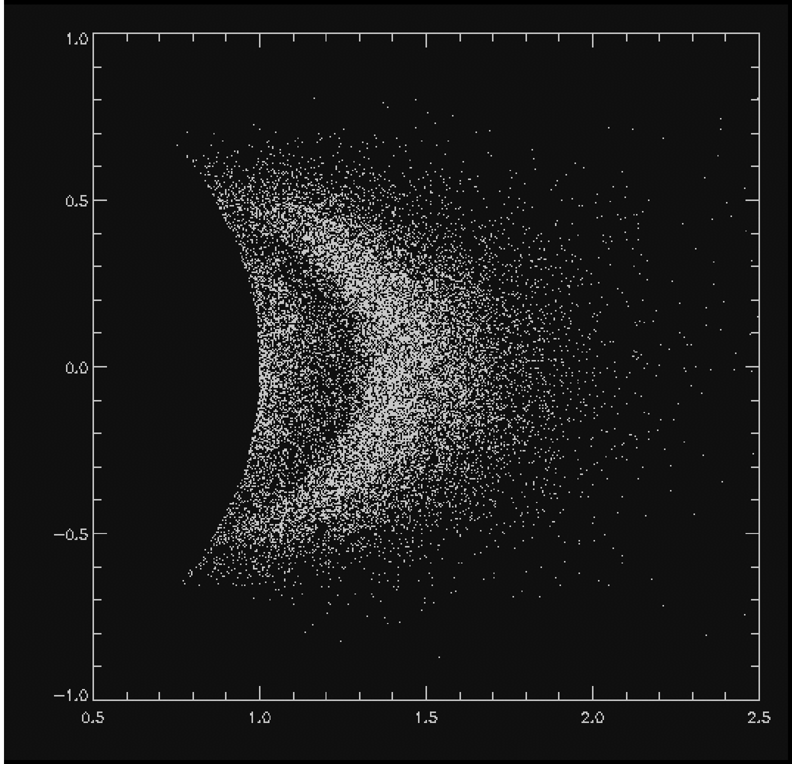
Is GJ picture really wrong?

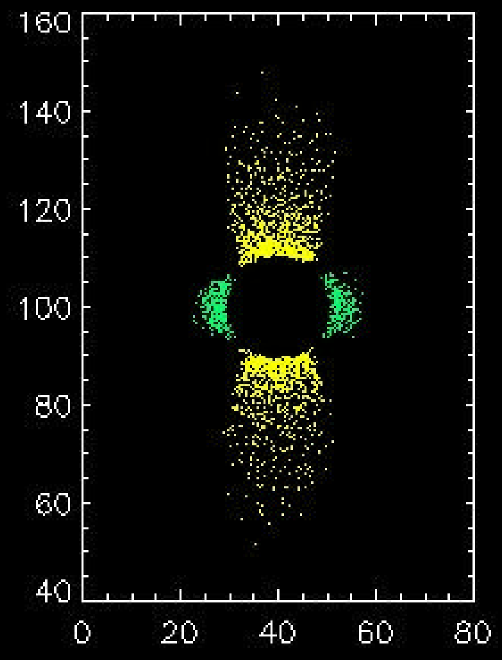
Movie: formation of electrosphere

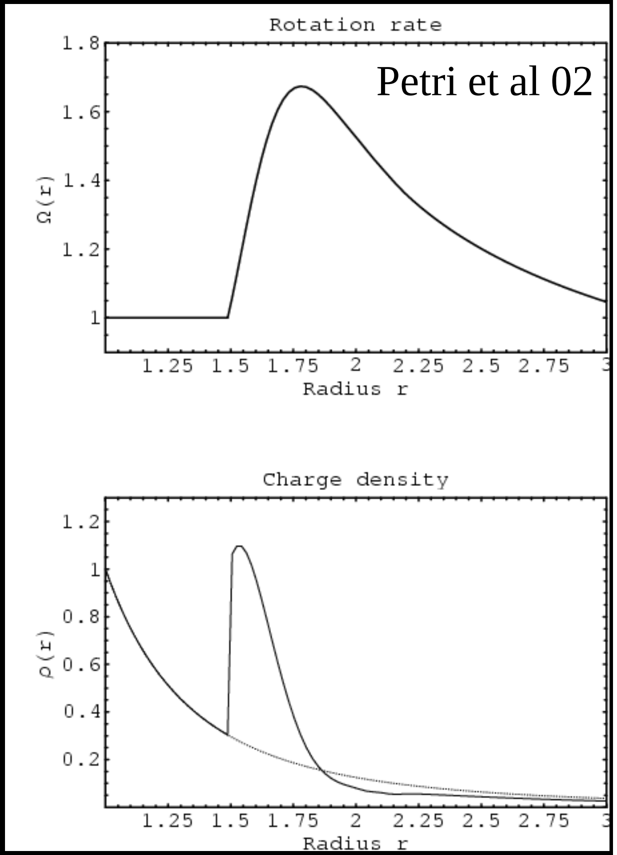


Aligned Rotator: electrospheres

Structure of the electrosphere





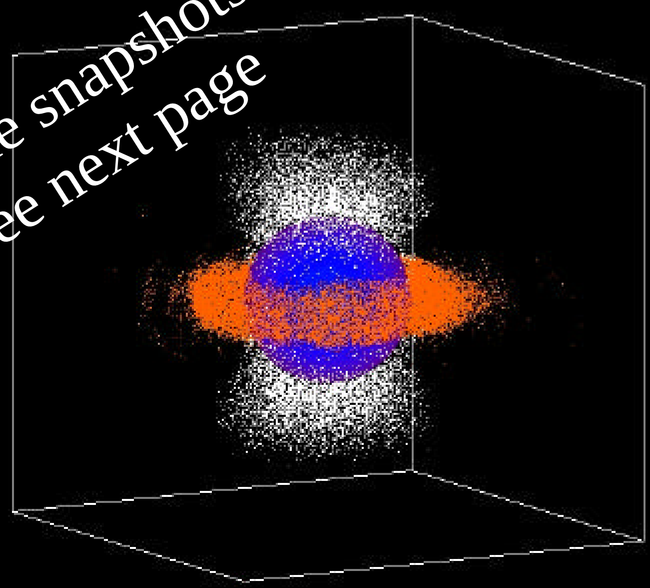


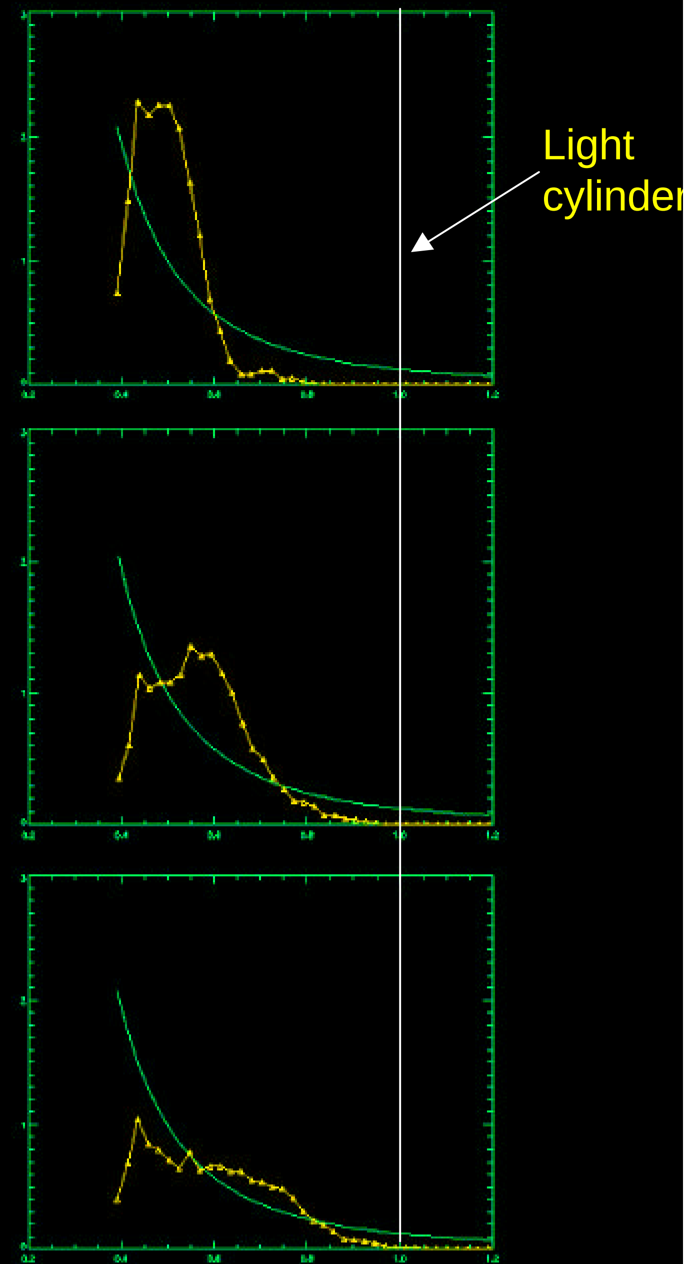
- Stationary solution -- emission stops. Stable to pair production in gaps
- Ion overdensity at 1.5 R -- differential rotation. Essential to have E*B=0.
- Field lines that are not filled with plasma to the star -- rotate differentially
- Dome in corotation at GJ density. Fieldlines shorted to the star.

Is the aligned rotator dead?

Aligned Rotator: going to 3D

Movie snapshots:
see next page



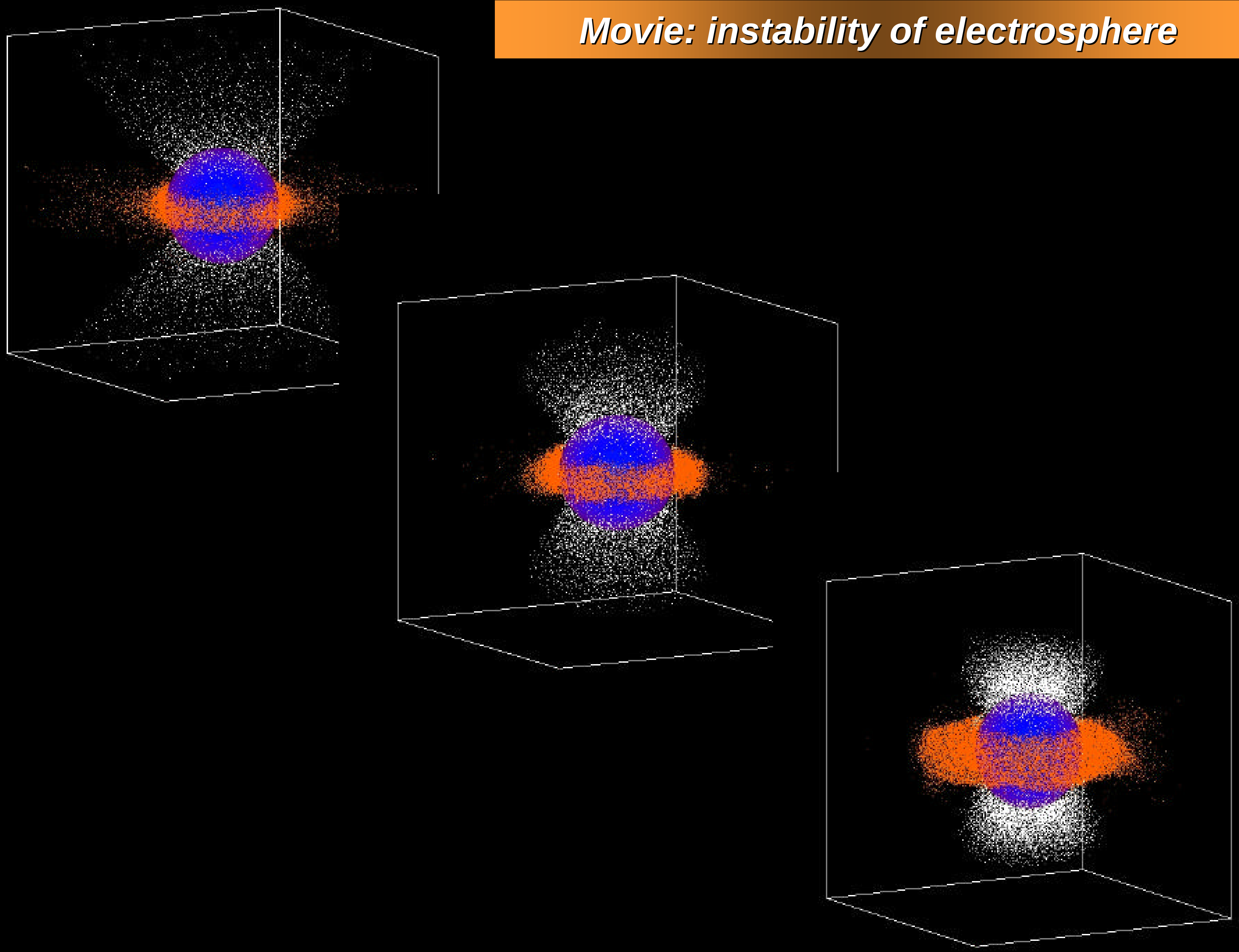


Can plasma fill the magnetosphere?

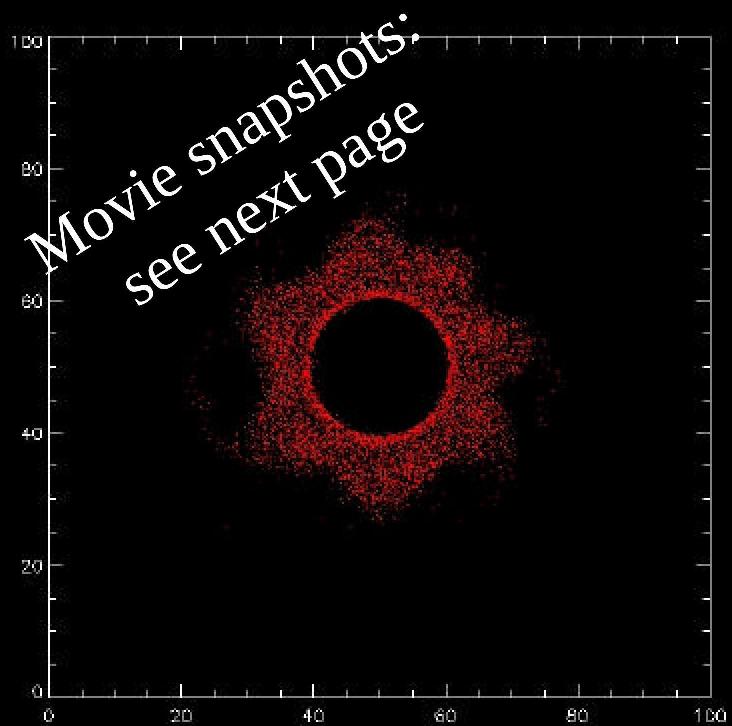
Not if it can't spread across the field lines!

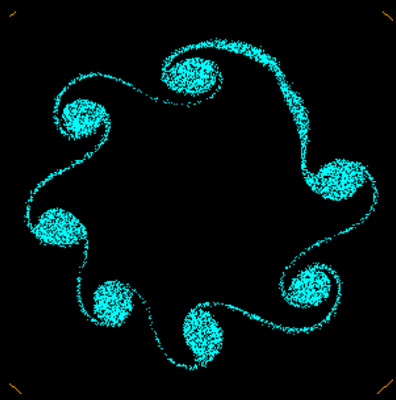
Plasma density(yellow) approaching GJ

Movie: instability of electrosphere



Aligned Rotator: going to 3D





Diocotron instability:

Particle dynamics is ExB drift.

Wavebreaking in the shearing flow similar to Kelvin-Helmholtz instability.

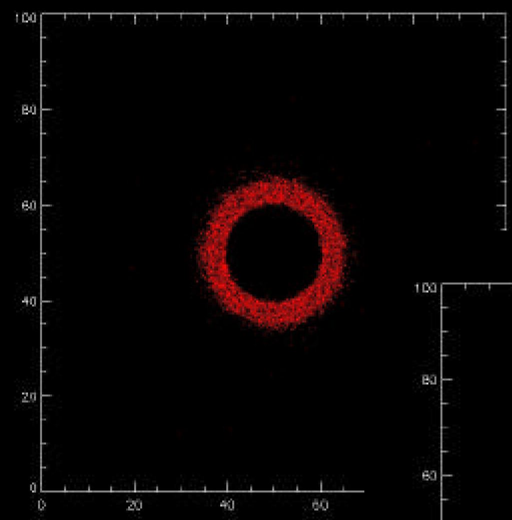
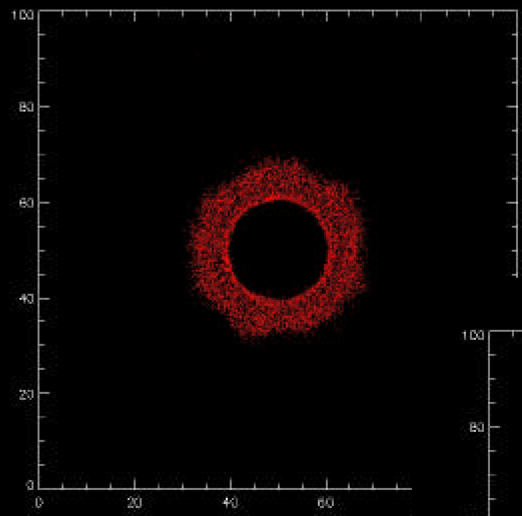
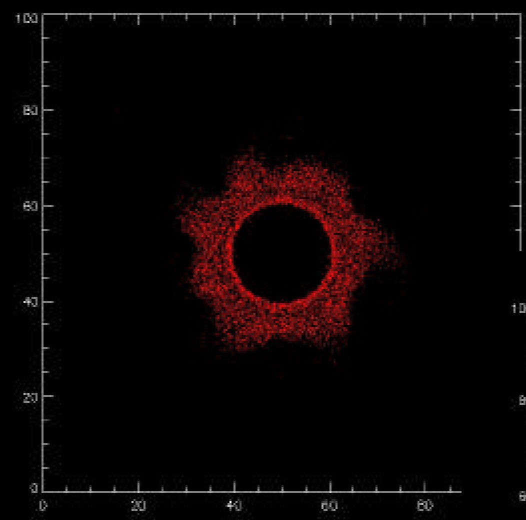
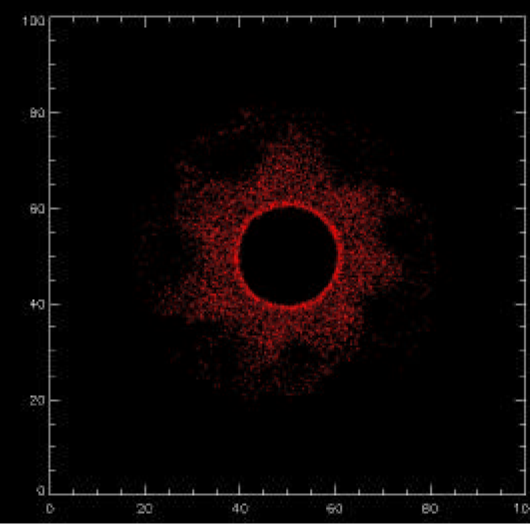
Azimuthal charge perturbation leads to radial ExB drift.

Typical unstable mode is a multiple of rotation frequency

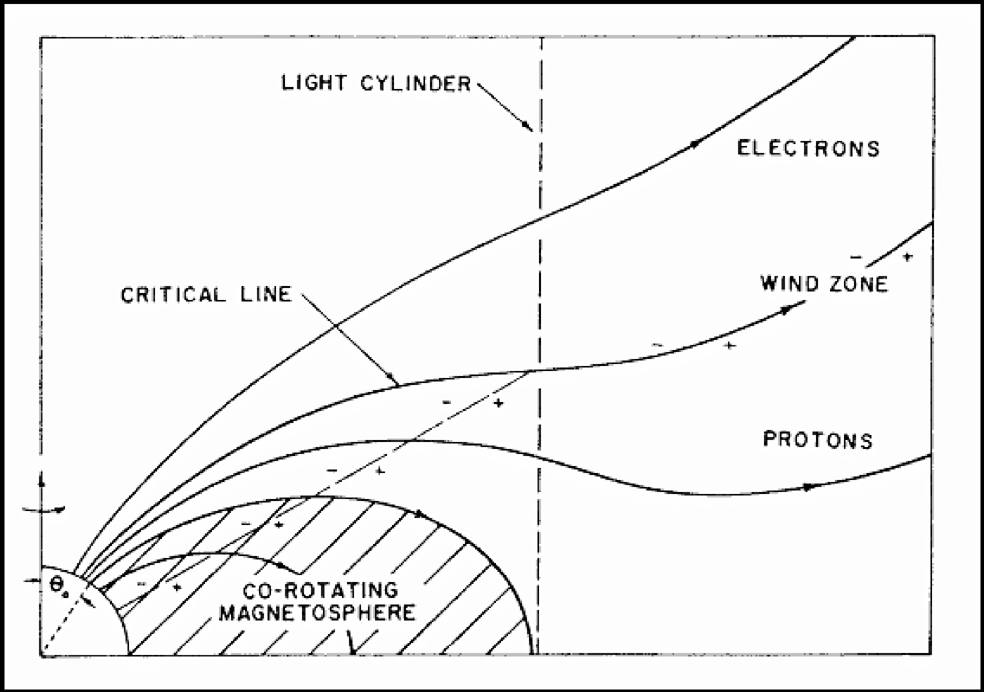
(diocotron frequency = $w_p^2 / 2w_c$)

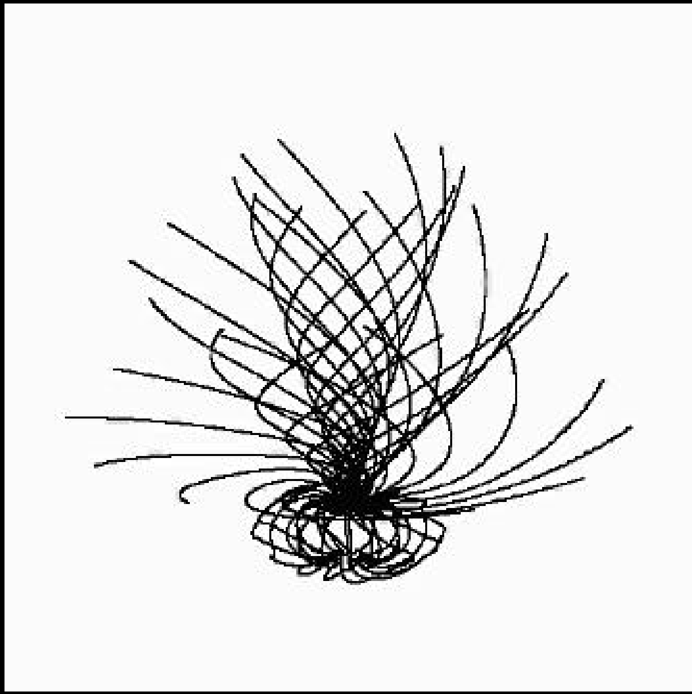
Grows in radius due to injection of new plasma from the surface

Movie: diocotron instability in equatorial plane

Implications for GJ model





If the closed zone cannot be supplied with GJ charge density from the star, the plasma near the star looses corotation and becomes unstable to diocotron instability which transports the charge to return magnetosphere to corotation.

Holloway's paradox resolved!

Conclusions and future work

Goldreich-Julian corotating magnetosphere is a dynamical consequence of the induced electric fields and plasma reaction in the dipole geometry

Charge adjustment in the closed zone is carried out via diocotron instability

Transport across magnetic field lines is possible even if the plasma is strongly magnetized

Modeling in full 3D is essential even for aligned rotators

In progress:

Magnetron instability: plasma rotation near light cylinder modifies the poloidal field.

Other types of emission: neutral plasma (pairs)

Obliquity introduces new effects such as wave pressure

Oblique Rotators: inclination 60 degrees