Electromagnetic hair of astrophysical black holes

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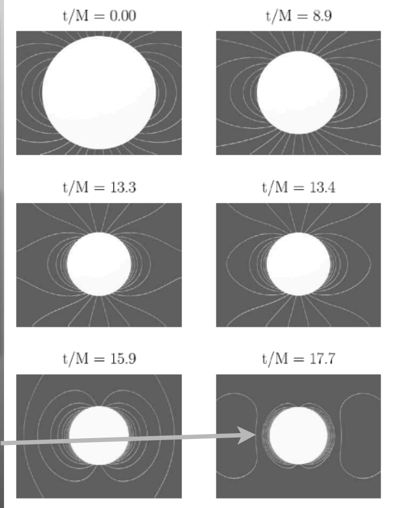
- The "no hair" theorem is not applicable to black holes formed from collapse of a rotating neutron star. Rotating neutron stars can self-produce particles via vacuum breakdown, forming a highly conducting plasma magnetosphere. As a result, magnetic field lines are effectively "frozen" into the star both before and during collapse. In the limit of no resistivity this introduces a topological constraint which prohibits the magnetic field from sliding off the newly-formed event horizon. The black hole's magnetosphere subsequently relaxes to the split monopole magnetic field geometry with self-generated currents outside the event horizon. The dissipation of the resulting equatorial current sheet leads to a slow loss of the anchored flux tubes, a process that balds the black hole on long resistive time scales rather than on the short light-crossing time scales expected from the vacuum "no-hair" theorem.

The "No hair" theorem

"No hair theorem": Isolated BH is defined by mass, angular momentum and electric charge.

Collapse of a magnetized NS into BH in vacuum: B-field is lost on ~ dynamic time



Such process is prohibited if outside is plasma

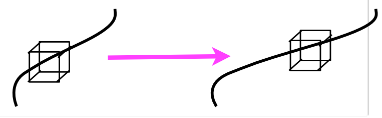
Baumgarte & Shapiro, 2003

Main point:

The proof of "no Hair" theorem assumes outside vacuum.

If outside plasma: **E.B** =0 - frozen-in B-field

This is a **topological** (not dynamic) constraint



- **Rotating** NS - unipolar inductor
  - generate plasma out of vacuum
  - have B-field lines open to infinity
- Blandford & Znajek: BHs do the same
- If a BH keeps producing plasma, like a NS, B-field cannot slide off**. E.B** =0: **field lines that connected NS surface to infinity, has to connect horizon to infinity**
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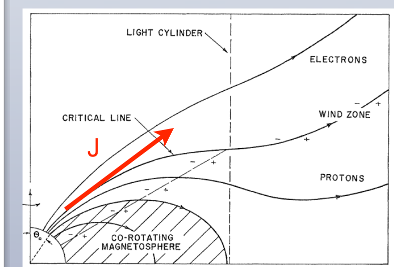


Goldreich & Julian, 1969

Main point:

- **The "no hair" theorem not applicable to collapse of rotating NSs: high plasma conductivity introduces topological constraint (frozen-in B-field).**

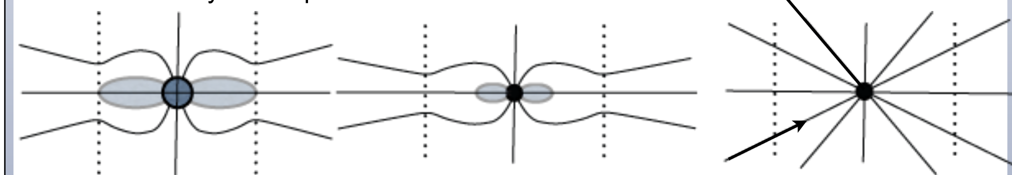
  Conserved number: open magnetic flux:

$$N_B = e\Phi_\infty/(\pi c\hbar)$$

$$\Phi_\infty \approx 2\pi^2 B_{NS} R_{NS}^3/(P_{\rm NS} c)$$

Property of horizon measurable at infinity: BH hair   Countable BH hair!

BHs can only have open field lines



Lyutikov 2011b

Time-dependent split-monopole solution in Schwarzschild metric

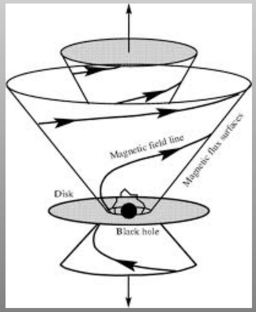
- Magnetosphere of collapsing NS:

$$B_\phi = -\frac{R_s^2 \Omega \sin\theta}{\alpha r} B_s, \quad B_r = \left(\frac{R_s}{r}\right)^2 B_s,$$

$$E_\theta = B_\phi, \quad j_r = -2\left(\frac{R_s}{r}\right)^2 \frac{\cos\theta \Omega B_s}{\alpha}$$

$$\Omega \equiv \Omega\left(r - t + r(1-\alpha^2)\ln(r\alpha^2)\right) \quad \alpha = \sqrt{1 - 2M/r}$$

$$B_s R_s^2 = const$$



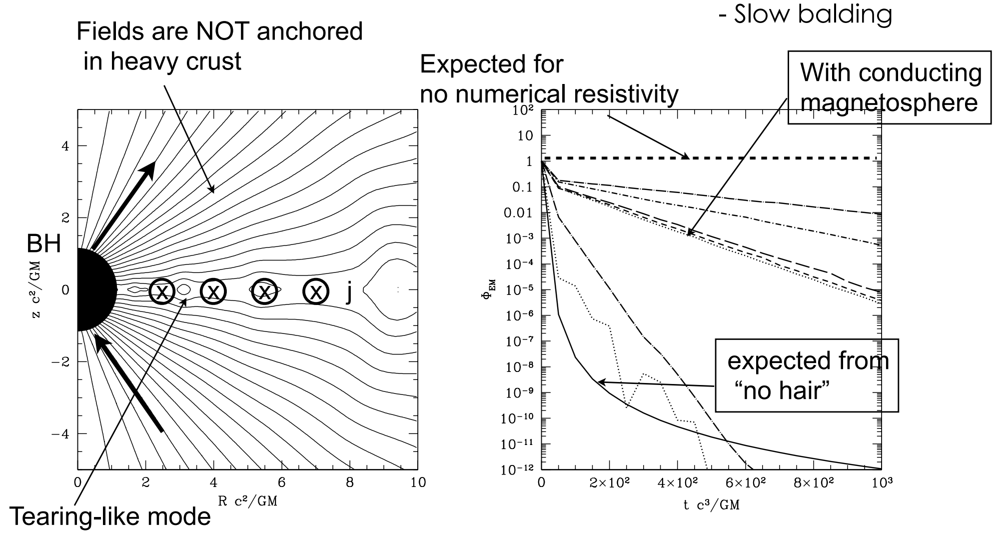
Take a relativistic object with monopolar B-field,
rotate it arbitrarily (slowly, a<< 1). The field will remain monopolar

Nothing “bad” happens to poloidal fields during NS collapse

Simulations *(Lyutikov & McKinney, 2011)*

-Split-monopole magnetosphere

- Slow balding



Fields are contained by the equatorial current, just like in BZ, but this current is self-produced

BZ parabolic solution: switch-off the disk -> relaxes to split monopole

Slowly balding black holes

As long as BH can produce pairs, open B-field lines do not slide off.

Field structure relaxes to split monopole

No need to anchor B-field into the heavy crust

Isolated BH acts as a pulsar, spins down electromagnetically, generates Poynting wind.

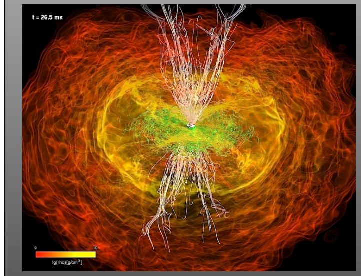
$$L \sim \frac{2}{3c}\left(\frac{\Phi\Omega_{BH}}{4\pi}\right)^2$$

Slow hair loss on **resistive** time scale - hard to predict

NB: Pair production by rotating BH on field lines penetrating the horizon is the key assumption of the Blandford-Znajek mechanism

The electromagnetic model of short GRBs

- NS-NS merger generates B ~ 10^{15} G in the torus around BH (Rezzolla et al.)
- BH-torus launches a jet along the axis: prompt spike
- After ~ 100 msec torus collapse, isolated BH spins down electromagnetically, produces **equatorially-collimated** flow, $L \propto \sin^2\theta$: prompt tail
- **Tail is more energetic**, but de-boosted for axial observer



Rezzolla et al