Electrodynamics of black holes

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Plan

- Astrophysical Introduction
- Unipolar Inductor
- Radio Pulsar Braking
- Black Hole Braking
- Conclusion

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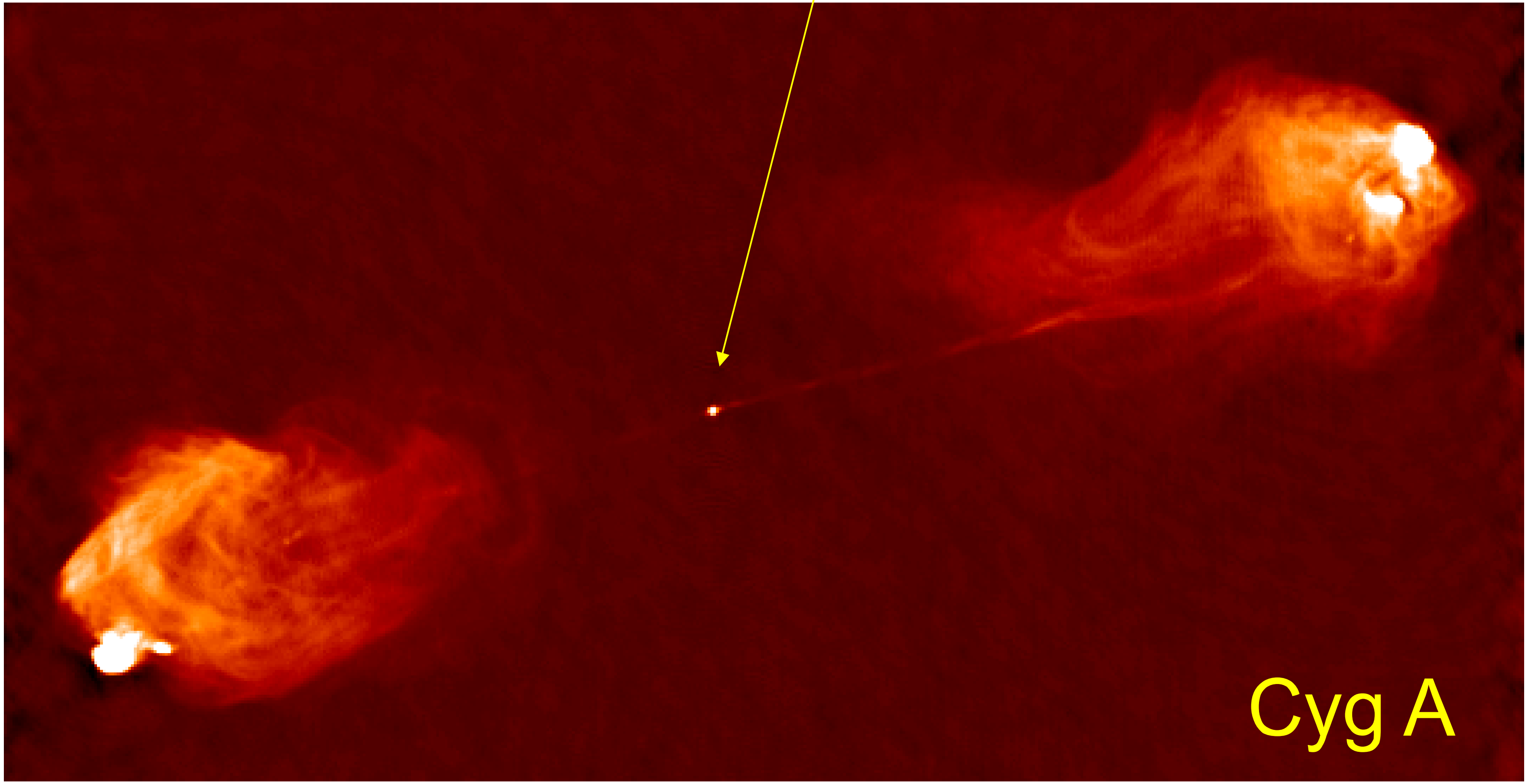
Astrophysical Introduction

- Active Galactic Nuclei
- Young Stellar Objects
- Radio Pulsars
- Microquasars

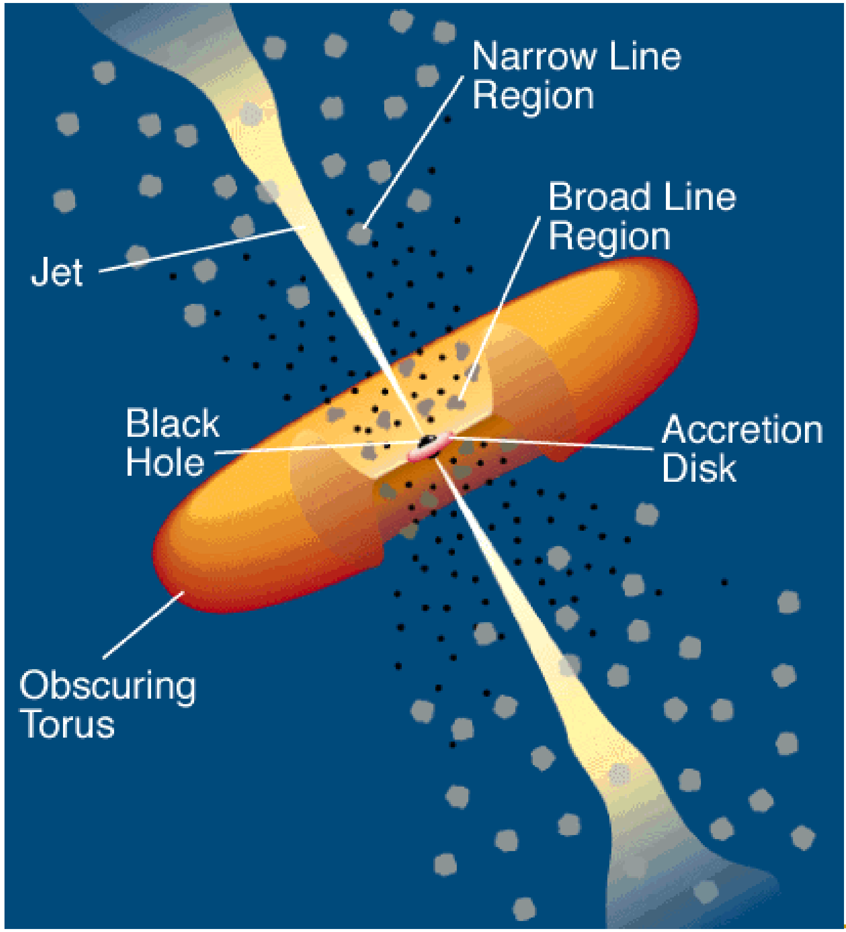
Most of them have jets

Active Galactic Nuclei (AGN)

$M \sim (10^8\text{-}10^9)M_\odot$, $R \sim 10^{13}$cm

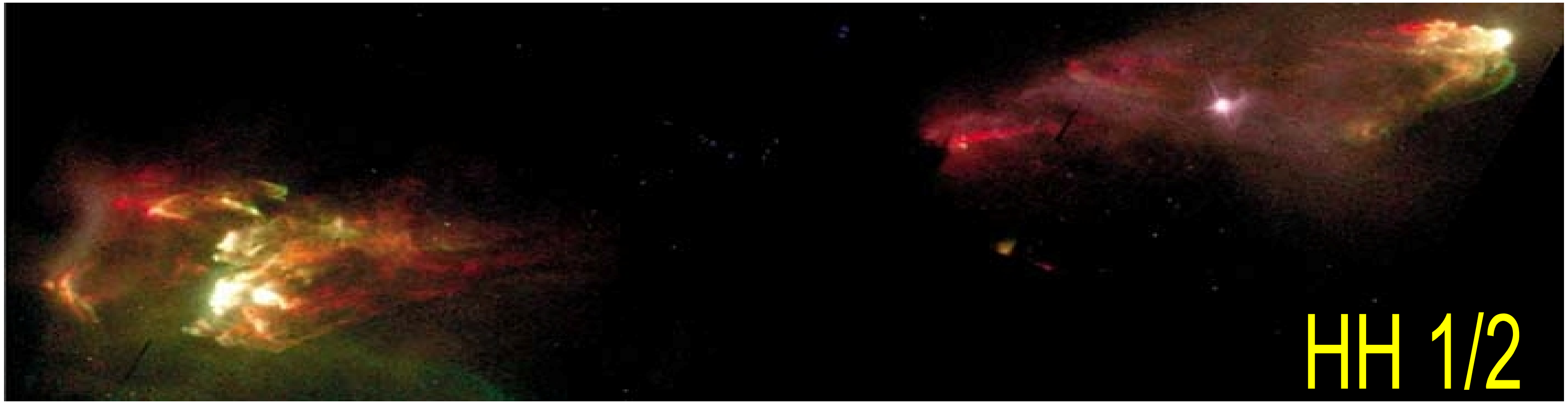


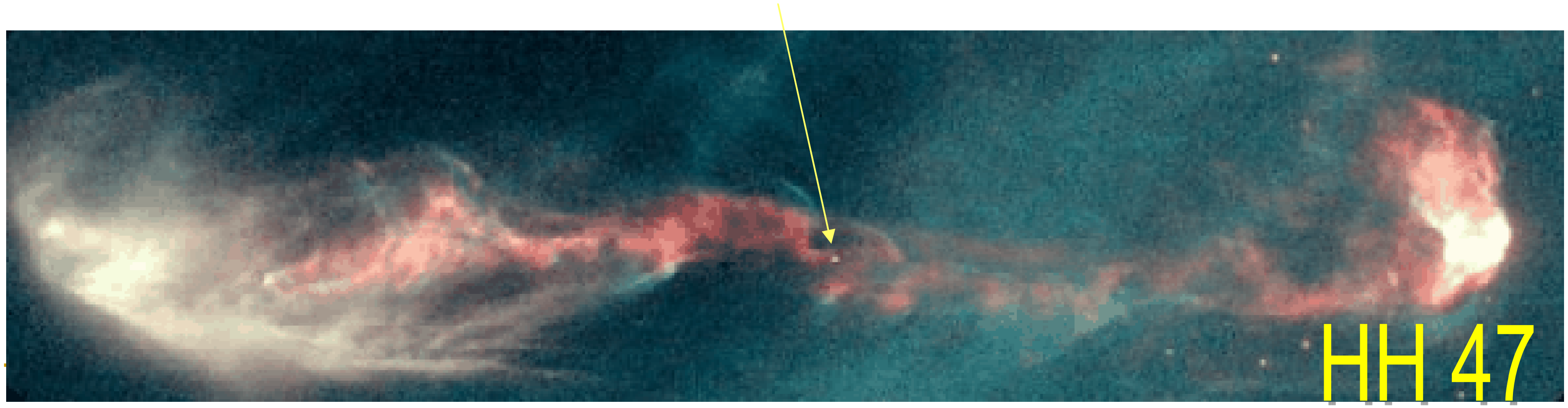
Active Galactic Nuclei (model)



Young Stellar Objects (YSO)

$M \sim 10 M_{\odot}$, $R \sim 10^{10}$cm





Young Stellar Objects (YSO)

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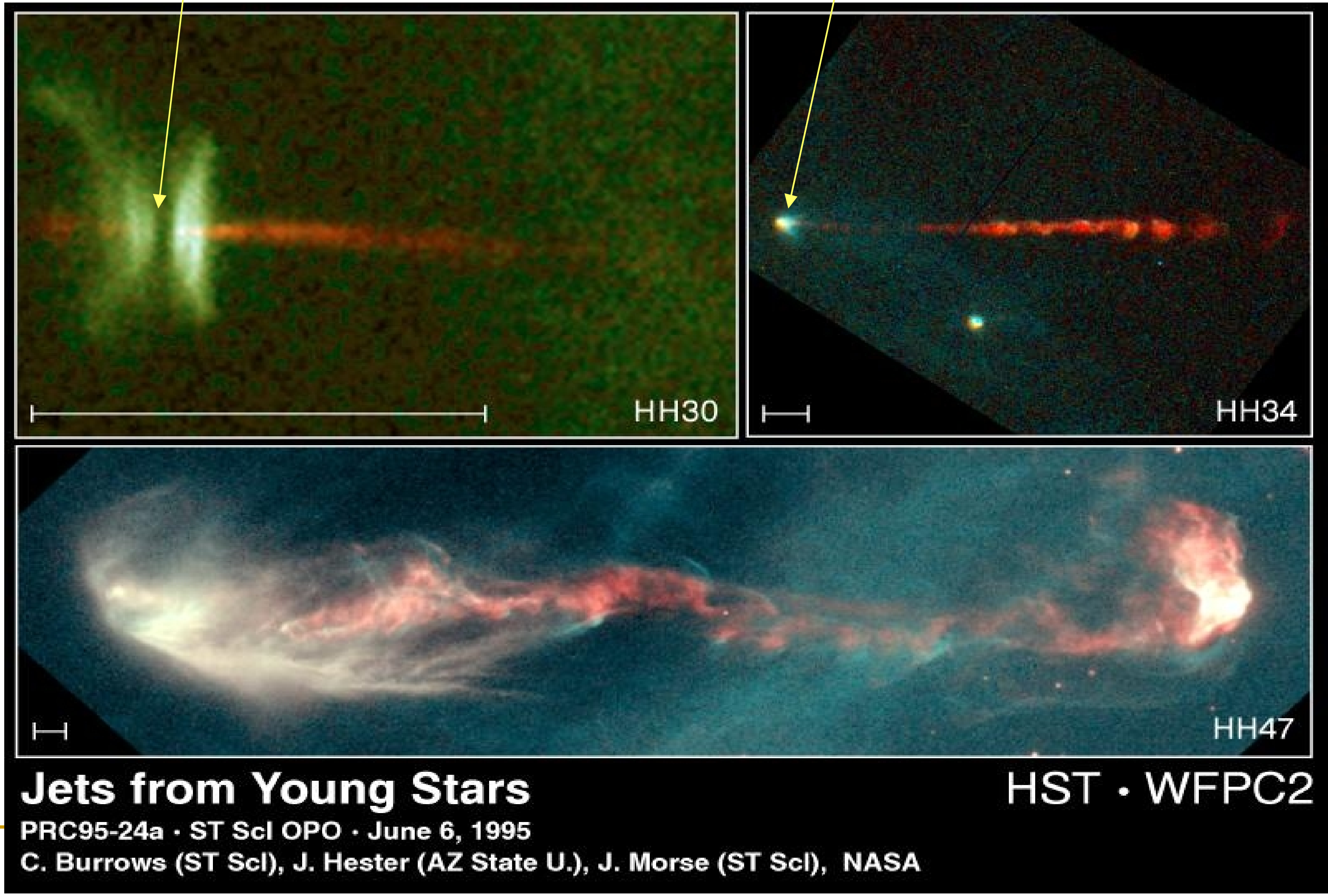
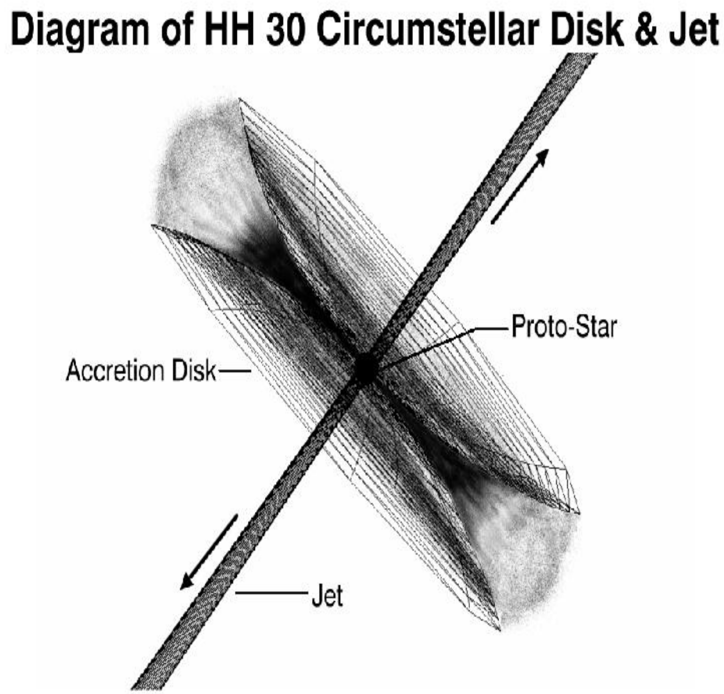
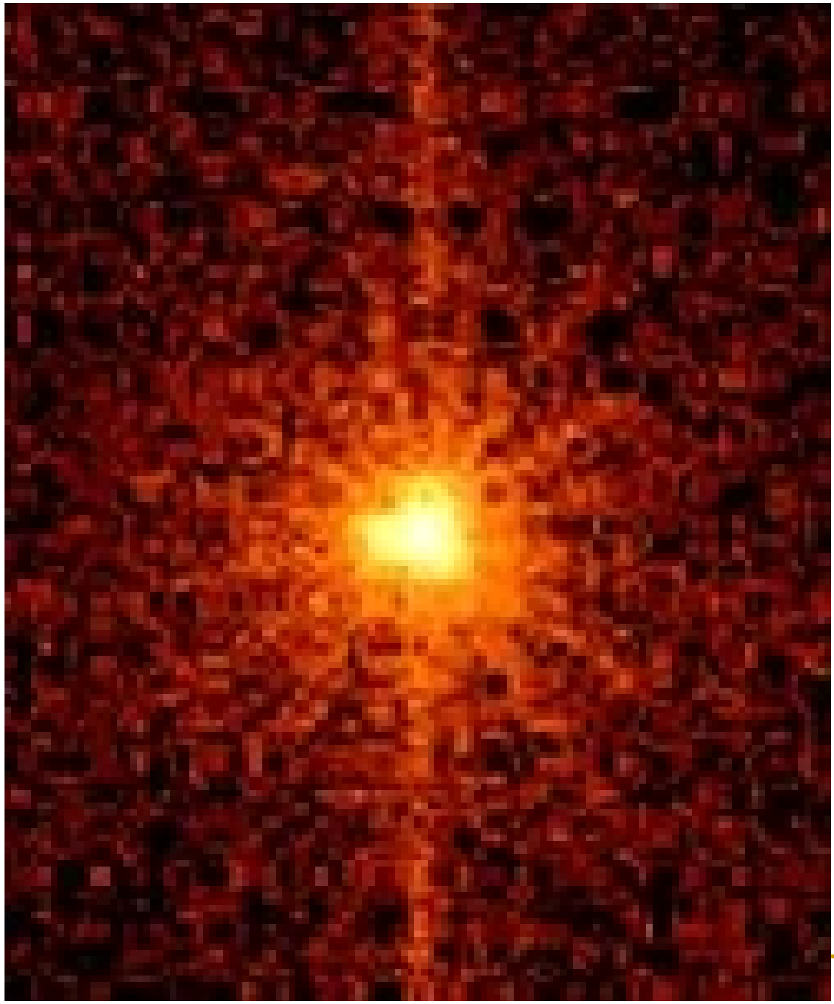


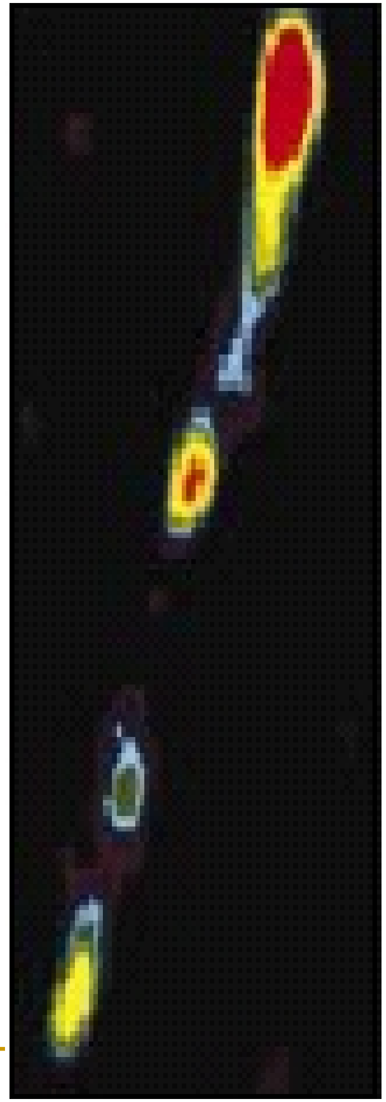
Young Stellar Objects (model)



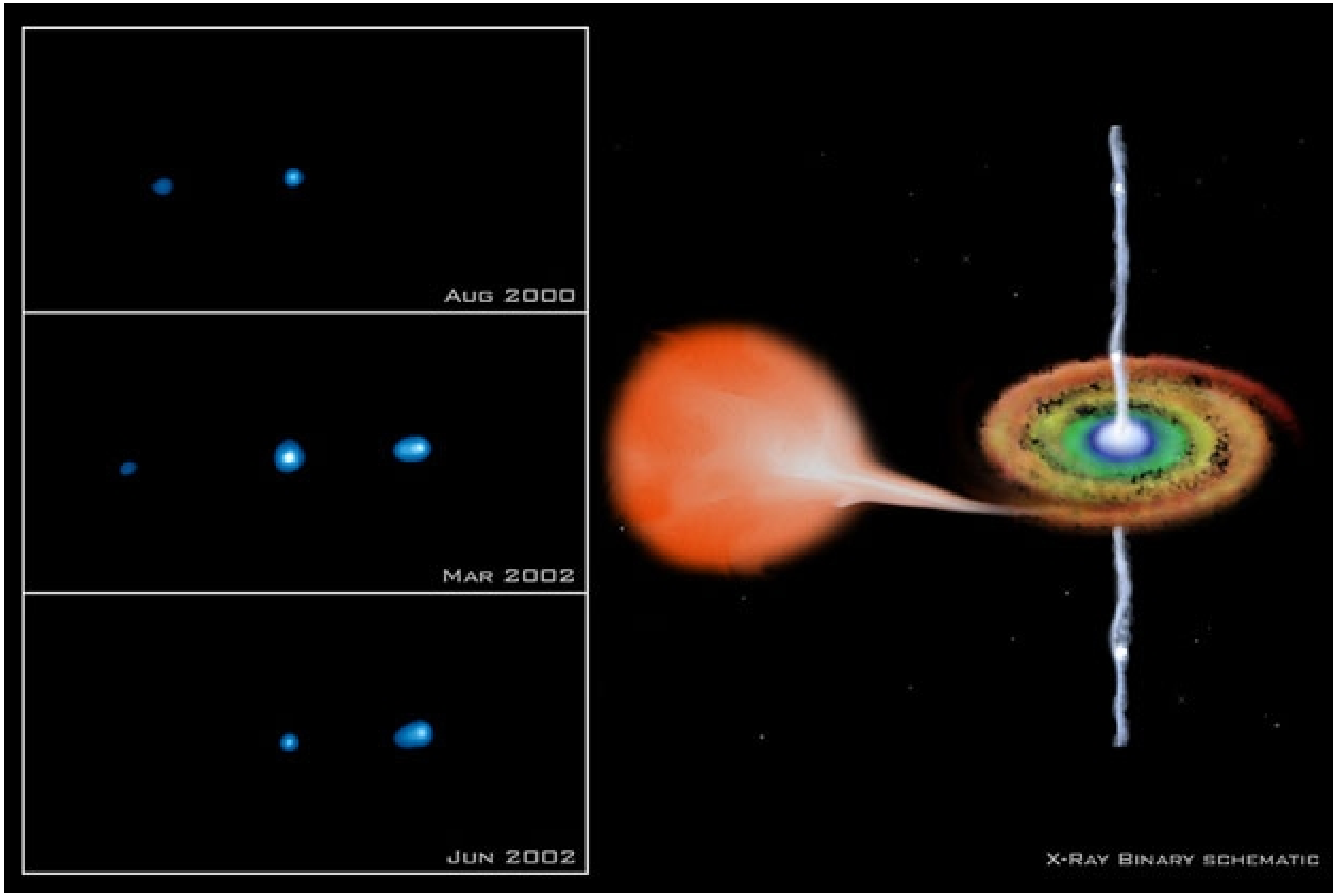
Microquasars (μQSO)

$M \sim (3\text{-}10)M_{\odot}$, $R \sim 10^6$cm

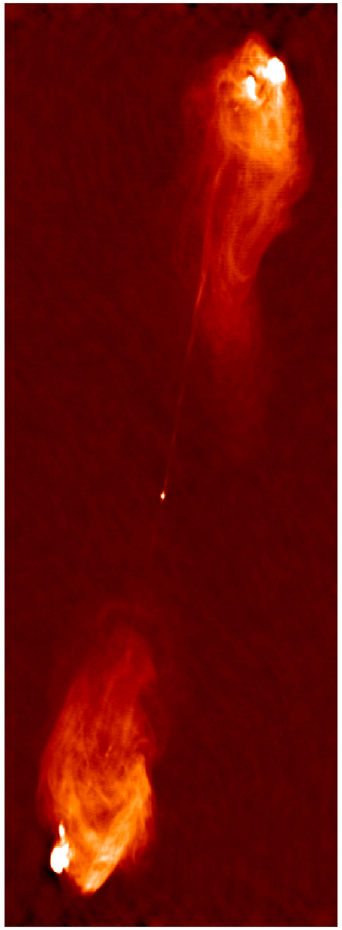


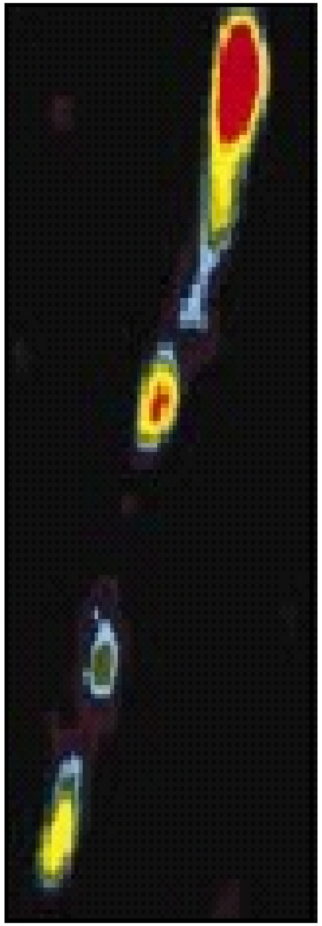


Microquasars (model)



The same mechanism?





The same mechanism?

- Thermal (gas pressure)?
- Radiative (radiation pressure)?
- Electromagnetic (Ampere force)?

Now it is not only the theoretical question

Radioastron -

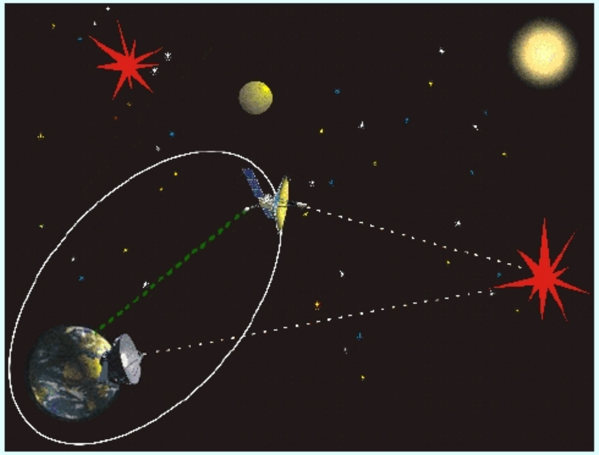
following parameters:

Perigee radius: ≥10,000 km

Initial inclination: 51.6^0

Average apogee radius: 350,000 km

Average period of revolution: 9.5 d



The ground-space radio interferometer (artist's view)

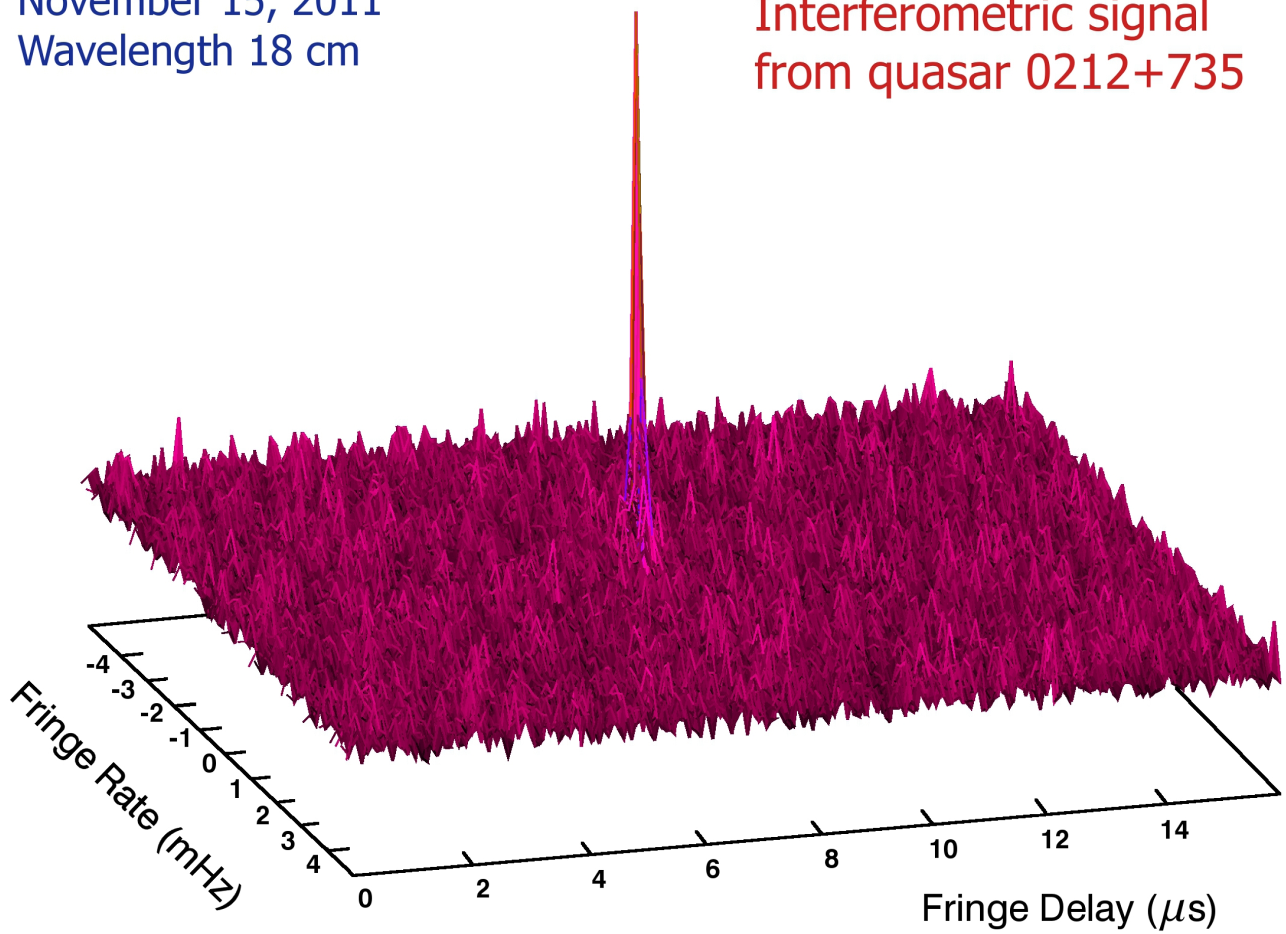
Band	P	L	C	K
Frequencies (MHz) of observations	327	1665	4830	18392-25112
Bandwidth (MHz) for each polarization	4	32	32	32
Fringe size (μas) [base line 350 000 km]	540	106	37	7,1 -10
Min. cor. flux (mJy) [RMS with EVLA, 300 s integration time]	10	1,3	1,4	3,2

Basic parameters of the Space Radio Telescope

100 000 km from Earth

November 15, 2011
Wavelength 18 cm

Interferometric signal
from quasar 0212+735

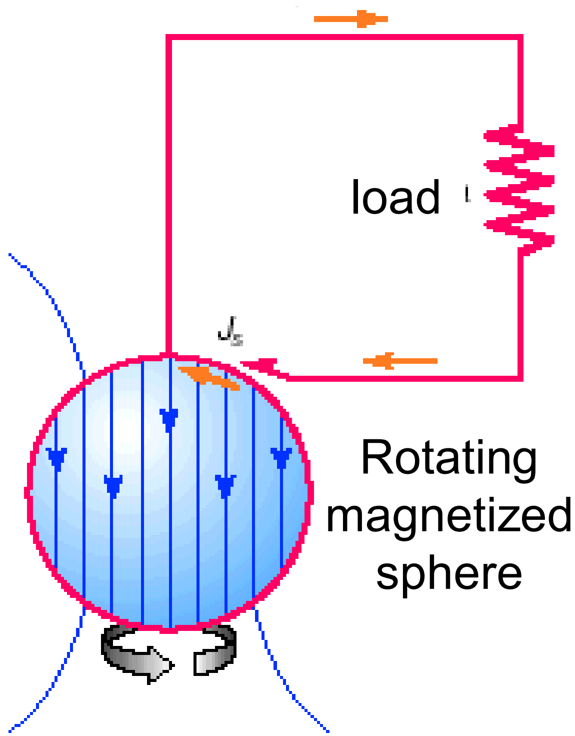


Unipolar Inductor

Rotating magnetized sphere can work as a battery (the source of the electric current)

Unipolar Inductor

1. Electric circuit is to be touched to the sphere at different latitudes.
2. Electric circuit is to rotate with the angular velocity Ω which differs from the angular velocity of a sphere.
3. The energy source is the kinetic energy of the rotation.
4. EMF does not result from the Faraday effect.



Unipolar Inductor (theory)

- Freezing-in condition

$$\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B}/c = 0 \qquad (\boldsymbol{E}' = \boldsymbol{j}/\sigma = 0)$$

- EMF (not connected with the Faraday effect)

$$E \sim (V/c)B, \qquad U = E\,L$$

- Nonzero charge density

$$\rho_{\mathrm{e}} \sim E/L \quad (E \sim Q/L^2) \qquad (\mathrm{div}\boldsymbol{E} = 4\pi\rho_{\mathrm{e}})$$

for rotation $V = \Omega r$

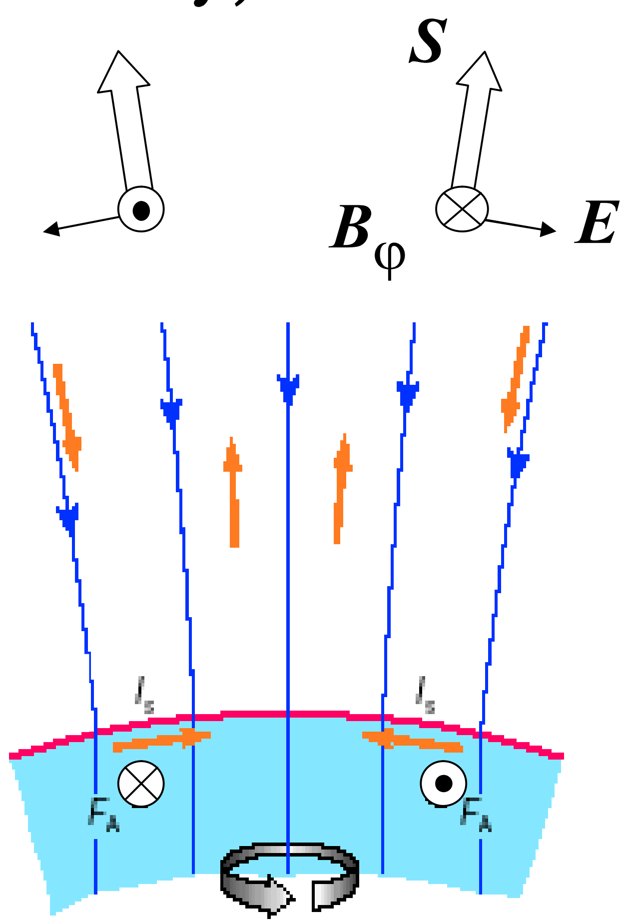
$$\boxed{\rho_{\mathrm{e}} = -\frac{\Omega B}{2\pi c}}$$

Radio Pulsar Braking

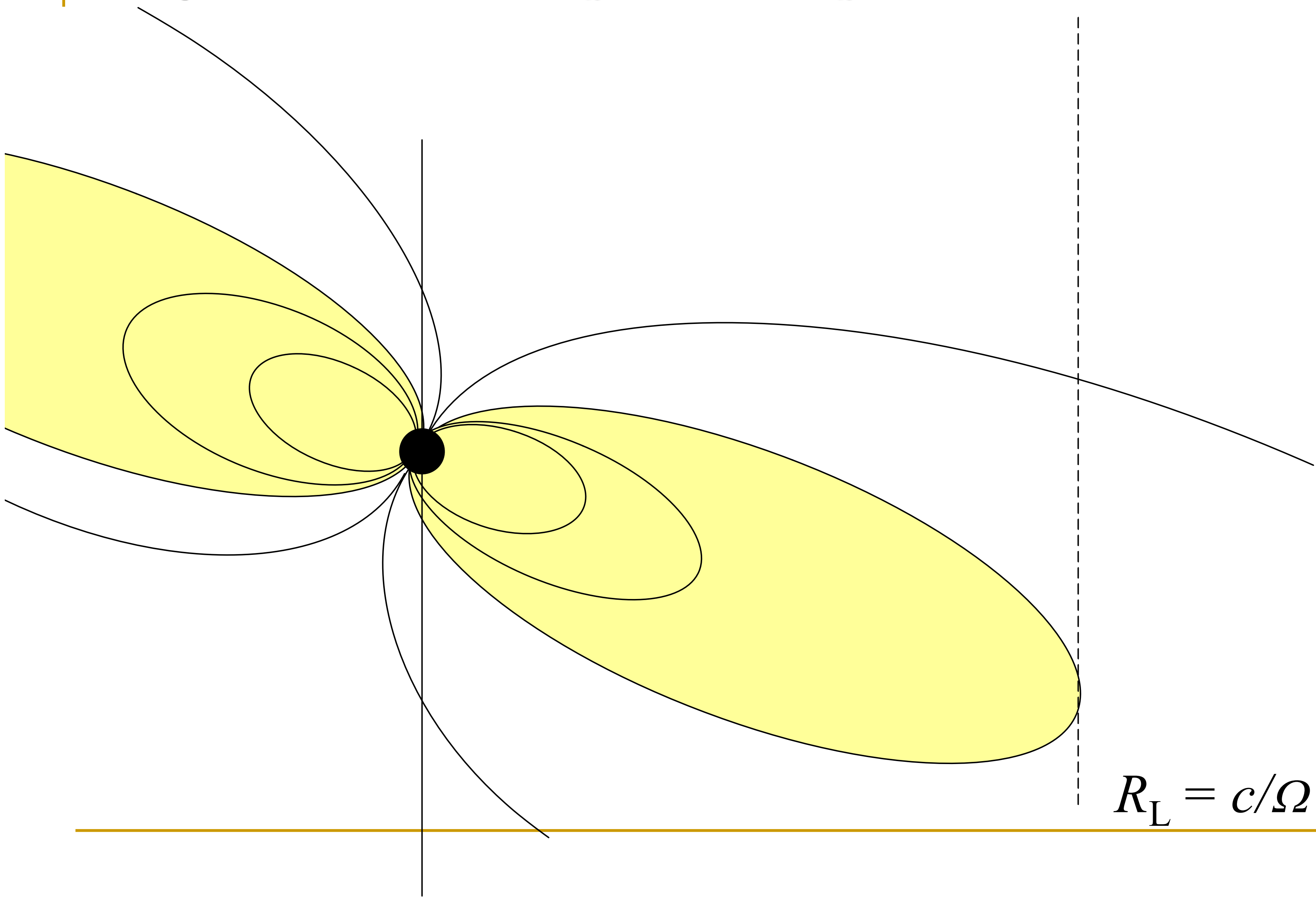
Rotating neutron star works as a unipolar inductor loosing its rotational energy by electric currents flowing in the magnetosphere.

Radio Pulsar Braking (theory)

1. Neutron star braking results from Ampere force
   $\boldsymbol{F}_A = (1/c)\, \boldsymbol{J}_s \times \boldsymbol{B}$
   of the surface currents $\boldsymbol{J}_s$ closing volume currents flowing in the magnetosphere.
2. Within light cylinder the energy flux is determined by the flux the electromagnetic energy
   $\boldsymbol{S} = (c/4\pi)\, \boldsymbol{E} \times \boldsymbol{B}$



Light cylinder, polar cap, corotation



Radio Pulsar Braking (theory)

- Corotation $\boldsymbol{V} = \boldsymbol{\Omega}\ \boldsymbol{r}$
- Light cylinder $R_L = c / \boldsymbol{\Omega}$
- Polar cap

$$R_0 \sim R\left(\frac{\Omega R}{c}\right)^{1/2}$$

- Energy loss $W = UI$

$$U \sim ER_0 \sim (\Omega R_0 / c) B_0 R_0$$

$$I \sim \rho_e c \pi R_0^2 \sim \Omega B_0 R_0^2$$

$$\boxed{W \sim B_0^2 \left(\frac{\Omega}{c}\right)^2 R_0^4 c \sim \frac{B_0^2 \Omega^4 R^6}{c^3}}$$

Radio Pulsar Braking (theory)

$$W \sim B_0{}^2 \left(\frac{\Omega R_0}{c} \right)^2 R_0{}^2 c$$

For radio pulsars

- magnetic field $B_0 \sim 10^{12}$ *G*
- neutron star radius $R \sim 10^6$ *cm*

the total energy loss $W \sim 10^{31} - 10^{33}$ *erg/s*
corresponds to $J_r \, \Omega \, \mathrm{d}\Omega/\mathrm{d}t$

Radio Pulsar Braking (theory)

For this mechanism is necessary to have

1. regular poloidal magnetic field,
2. rotation (inductive electric field ***E*****,** EMF U),
3. longitudinal current I (toroidal magnetic field B_φ).

Black Hole Braking

- Rotating black hole
- “No hair” theorem
- Blandford-Znajek process
- A problem
- The answer

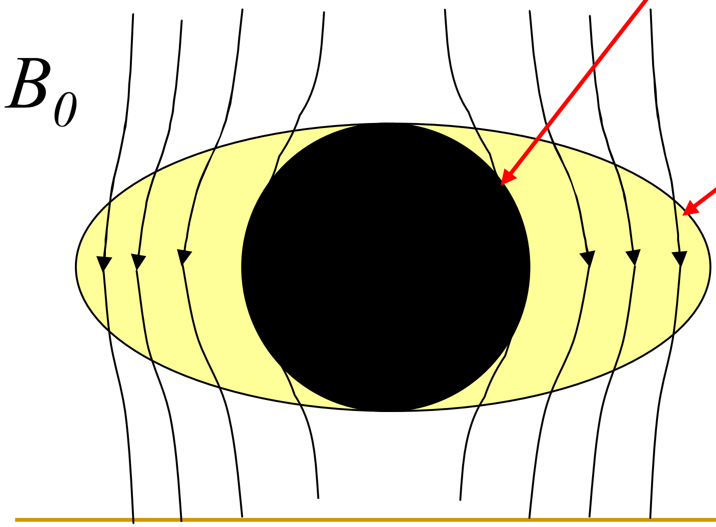
Rotating Black Hole

Gravitational radius

$$r_g = G/c^2[M + (M^2 - a^2)^{1/2}]$$

Ergosphere

$$r_e = G/c^2[M + (M^2 - a^2\cos^2\theta)^{1/2}]$$



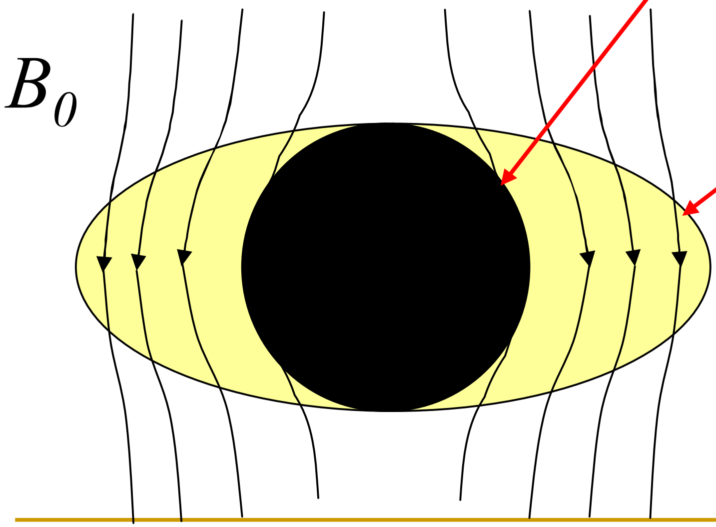
Rotating Black Hole

Gravitational radius

$r_g = \quad M + (M^2 - a^2)^{1/2}$

Ergosphere

$r_e = \quad M + (M^2 - a^2 cos^2 \theta)^{1/2}$



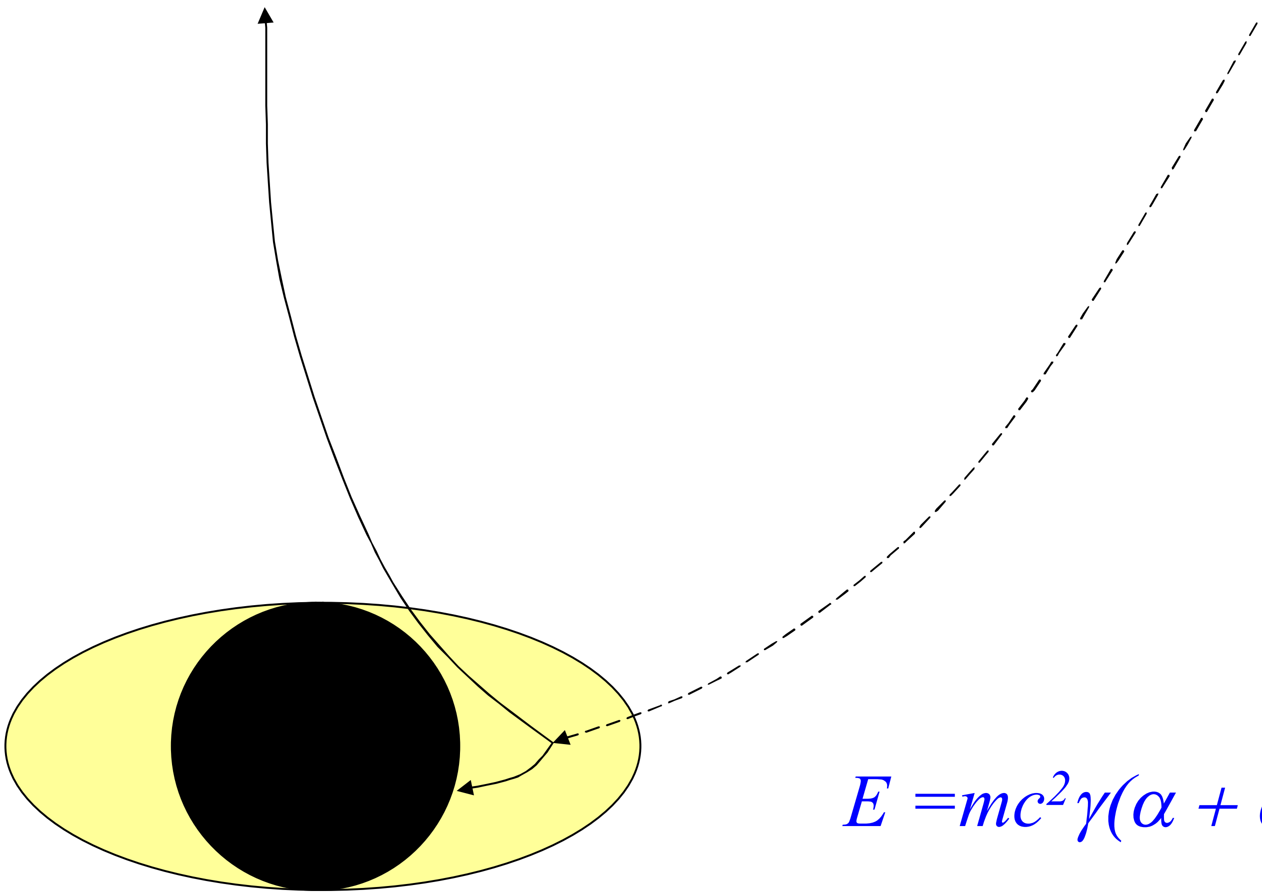
Frame-dragging (Lense-Thirring effect)

Inside the ergosphere any body (including the light) is to rotate with the black hole.
More important. At all distances “the rotation of the space” takes place. Thus, there are a distinguished reference frame rotating with Lense-Thirring angular velocity

$$\omega \sim \Omega_H (r_g/r)^3$$

ZAMO (no gyroscope rotation).

Penrose process



$$E = mc^2\gamma(\alpha + \omega\,\varpi\,v_\varphi/c^2)$$

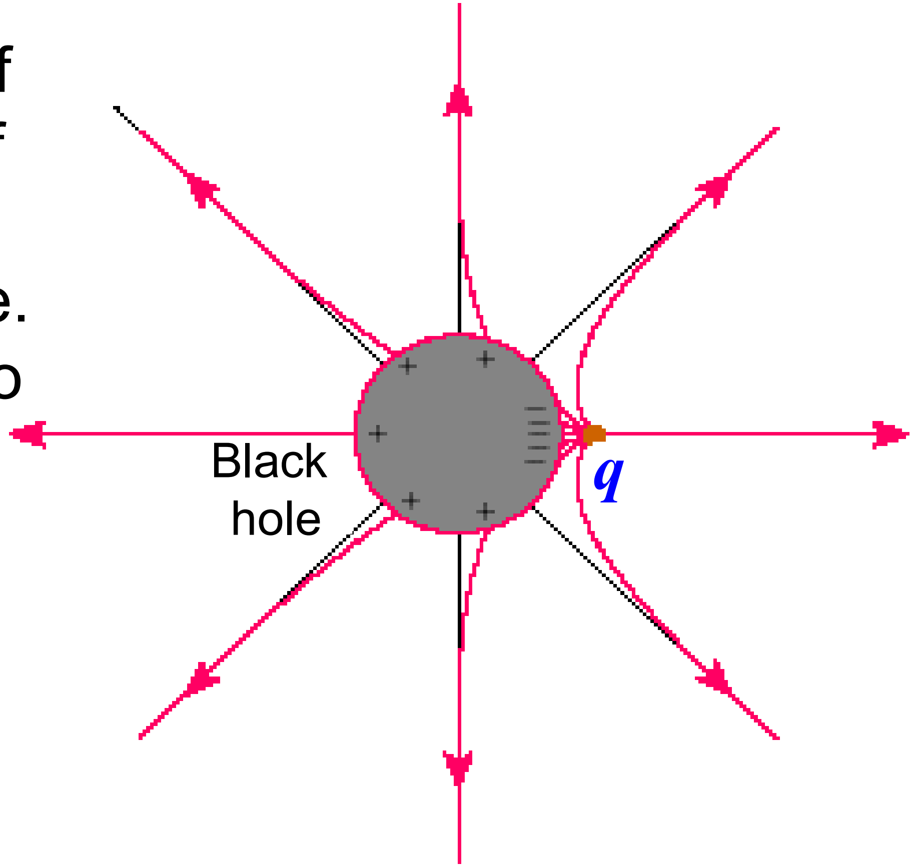
$$g_{\varphi\varphi} = \varpi^2$$

“No hair” theorem

Black hole cannot have its own magnetic field.
But it can be submerged into the external magnetic field generated e.g. in the accretion disk.

"No hair" theorem

1. Electric field of a charge q located in the very vicinity of the horizon looks like that of the charge q located in the very center of the black hole.
2. Thus, the electric field of two different charges (a dipole) vanishes as the charges approach themselves to the horizon.
3. The same for the magnetic dipole, quadrupole, *etc*.

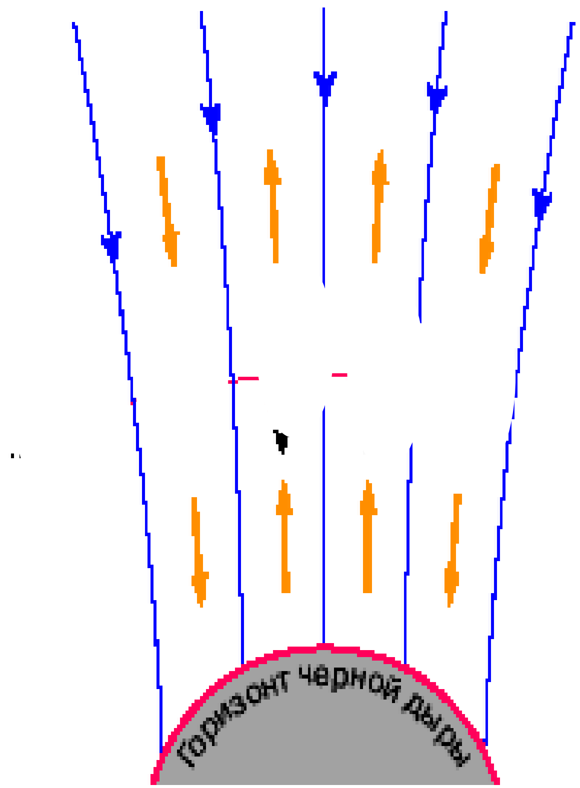


Blandford – Znajek process (1977)

The analogy with radio pulsars

1. External poloidal magnetic field (generated in a disk).
2. Rotation of a black hole.
3. Longitudinal current I.

$$W_{\mathrm{BZ}} \sim B_0{}^2 \left(\frac{\Omega R_g}{c} \right)^2 R_g{}^2 c$$



Blandford – Znajek process (1977)

$$W_{\mathrm{BZ}} \sim B_0^{\ 2}\left(\frac{\Omega R_g}{c}\right)^2 R_g^{\ 2} c$$

For the central engine in active galactic nuclei

- magnetic field B_0 *~10⁴ G*
- black hole radius R_g *~ 10¹³ cm*

the total energy loss W *~ 10⁴⁵ erg/s*
is in agreement with observations.

Blandford – Znajek process (1977)

The analogy with radio pulsars

1. The energy flux is determined by the Poynting flux $\boldsymbol{S} = (c/4\pi)\, \boldsymbol{E} \times \boldsymbol{B}$.
2. Black hole braking results from Ampere force $\boldsymbol{F}_{\mathrm{A}} = (1/c)\, \boldsymbol{j} \times \boldsymbol{B}$ of the surface currents closing volume currents flowing in the magnetosphere.
3. It’s necessary to add the boundary condition on the horizon fixing the structure of the magnetic field (actually, to introduce the surface conductivity).

Blandford – Znajek process (1977)

The analogy with radio pulsars

1. The energy flux is determined by the Poynting
   flux S = (c
2. Black hole … mpere force
   $F_A = (1/c)\, j$ … ents closing
   volume cu … gnetosphere.
3. It's necess … y condition on
   the horizon … the magnetic
   field (actua … face
   conductivity).

B.Punsly

The problems

The horizon isn’t in casual connection with the outer space*.
The horizon isn’t a material boundary of a black hole*.
Black hole cannot be a battery (the source of the exterior forces)*.

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* They are very serious objections.

The problems

Poynting flux

$\boldsymbol{S} = (c/4\pi)\, \boldsymbol{E} \times \boldsymbol{B}$

directs downwards in the very vicinity of the horizon.

The answer (1)

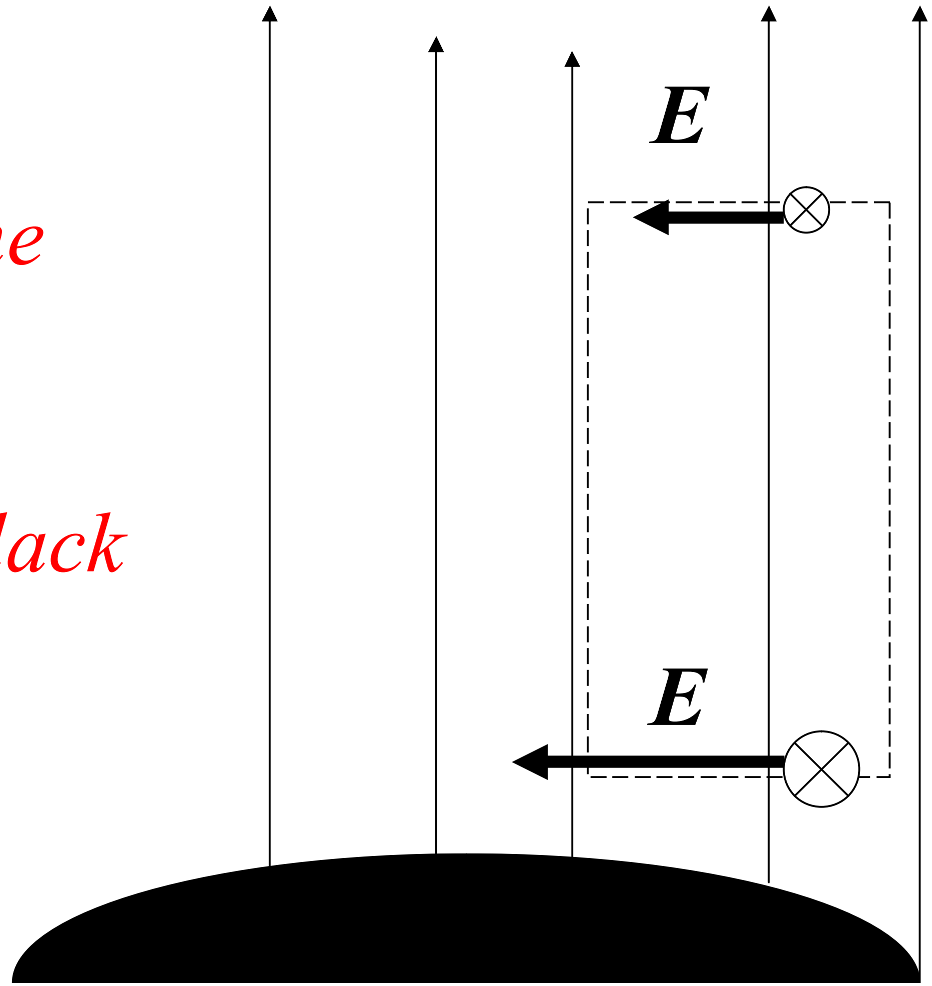
- EMF results from the Lense-Thirring effect, not the exterior forces inside the black hole.
- Frame dragging results in “the flow of the space” through any circuit which is equivalent to alternative magnetic flux.
- EMF appears over the horizon.

The answer (1)

The motion relatively ZAMOs results in the generation of the electric field.

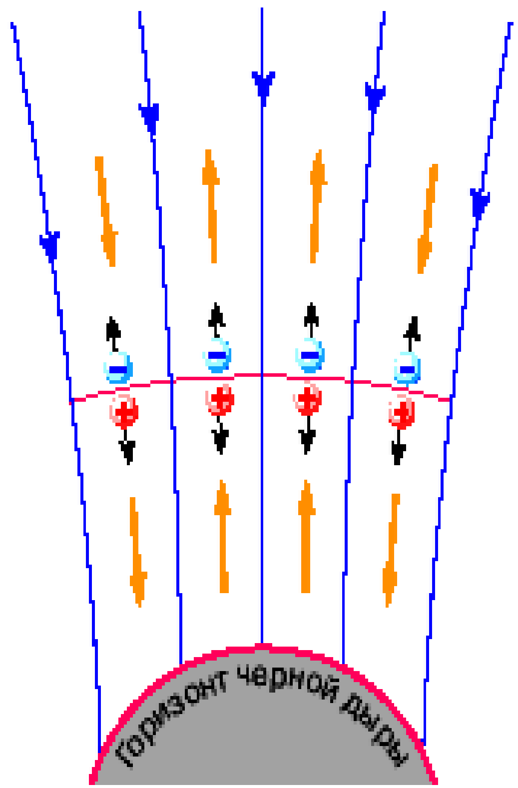
$$\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}/c$$

EMF results from the different velocity of ZAMOs at different distances from the black hole.



Blandford – Znajek process

- To realize electric current it's necessary to create pairs above the horizon
- Blandford-Znajek process is electromagnetic realization of Penrose process



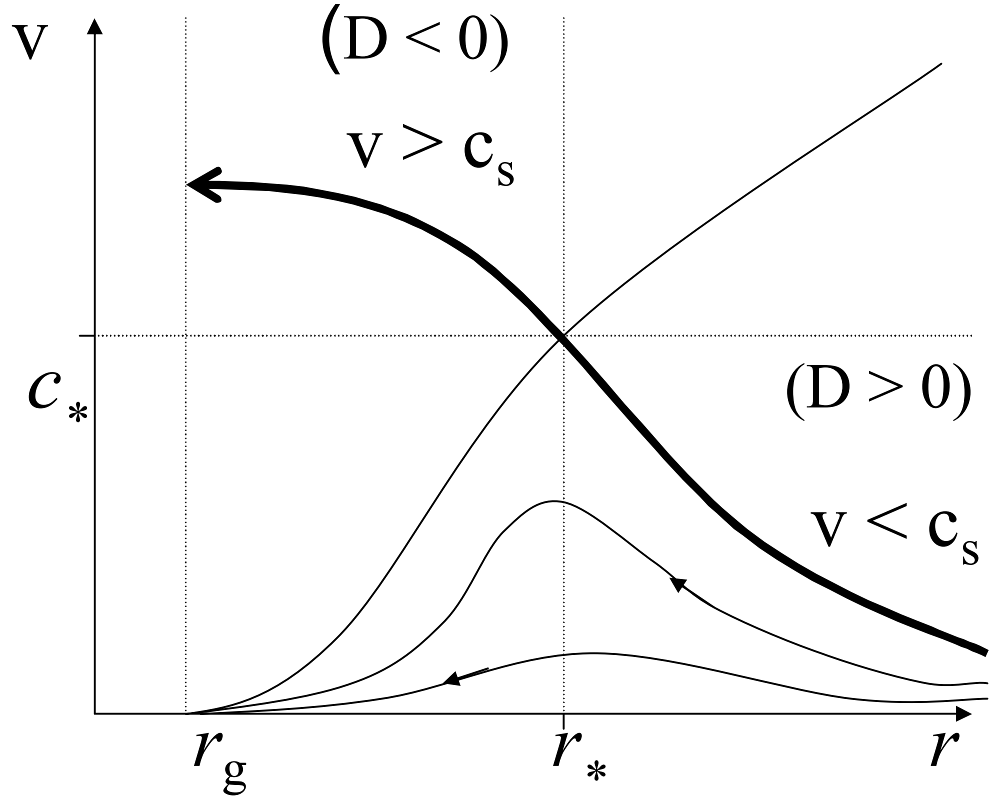
Bondi accretion onto black hole

The transonic flow
only is possible.

$\mathrm{v}\,(r_g) > 0$ means

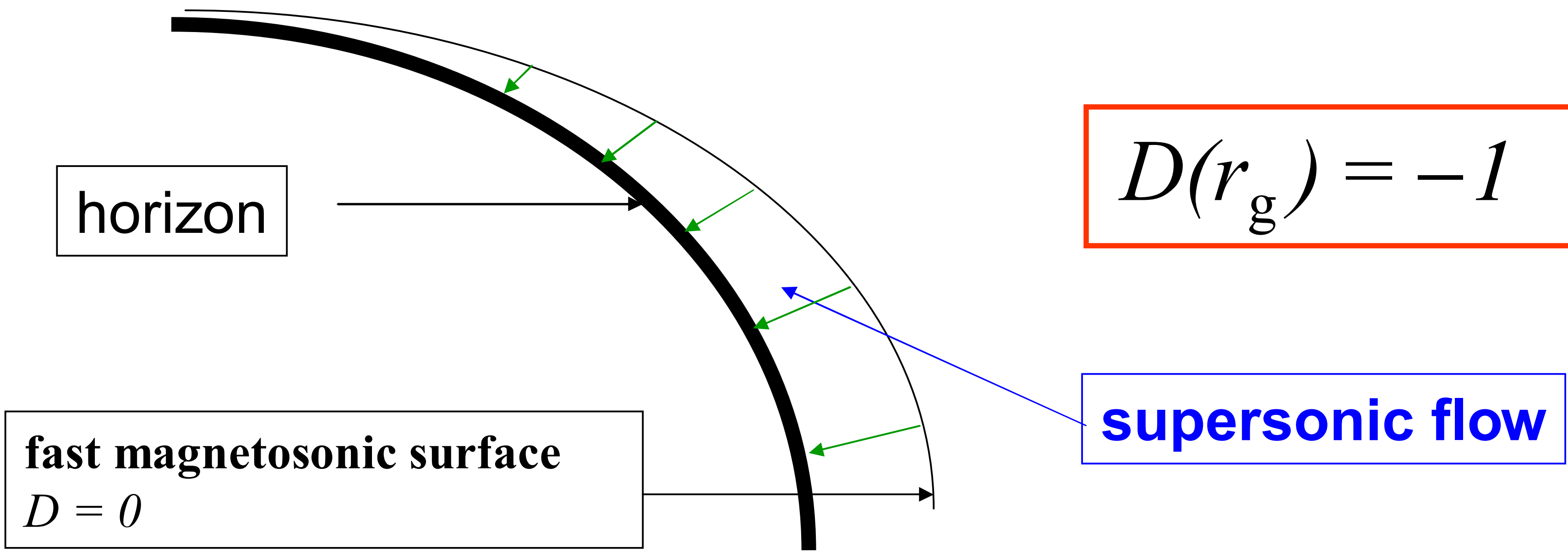
$\mathrm{v}\,(r_g) > c_* \,.$

The critical condition fixes the accretion rate.



Force-free limit

Force-free limit of the critical condition on the fast magnetosonic surface is “the boundary condition on the horizon”



$$D(r_g) = -1$$

Grad-Shafranov equation in Kerr metric

$$\boxed{\begin{aligned} &A\left[\frac{1}{\alpha}\nabla_k\left(\frac{1}{\alpha\varpi^2}\nabla^k\Psi\right)+\frac{1}{\alpha^2\varpi^2}\frac{\nabla^i\Psi\cdot\nabla^k\Psi\cdot\nabla_i\nabla_k\Psi}{(\nabla\Psi)^2 D}\right] \\ &-\frac{A\nabla'_k F\cdot\nabla^k\Psi}{2\alpha^2\varpi^2(\nabla\Psi)^2 D}+\frac{\nabla'_k A\cdot\nabla^k\Psi}{\alpha^2\varpi^2}+\frac{(\Omega_\mathrm{F}-\omega)}{\alpha^2}(\nabla\Psi)^2\frac{\mathrm{d}\Omega_\mathrm{F}}{\mathrm{d}\Psi} \\ &+\frac{32\pi^4}{\alpha^2\varpi^2\mathbf{M}^2}\frac{\partial}{\partial\Psi}\left(\frac{G}{A}\right)-16\pi^3\mu n\frac{1}{\eta}\frac{\mathrm{d}\eta}{\mathrm{d}\Psi}-16\pi^3 nT\frac{\mathrm{d}s}{\mathrm{d}\Psi}=0 \end{aligned}}$$

$$D=\frac{A}{\mathbf{M}^2}+\frac{\alpha^2}{\mathbf{M}^2}\frac{B_\varphi{}^2}{B_\mathrm{p}{}^2}+\frac{1}{u_\mathrm{p}{}^2}\frac{A}{\mathbf{M}^2}\frac{c_s{}^2}{1-c_s{}^2};\mathbf{M}^2=\frac{4\pi\mu\eta^2}{n}$$

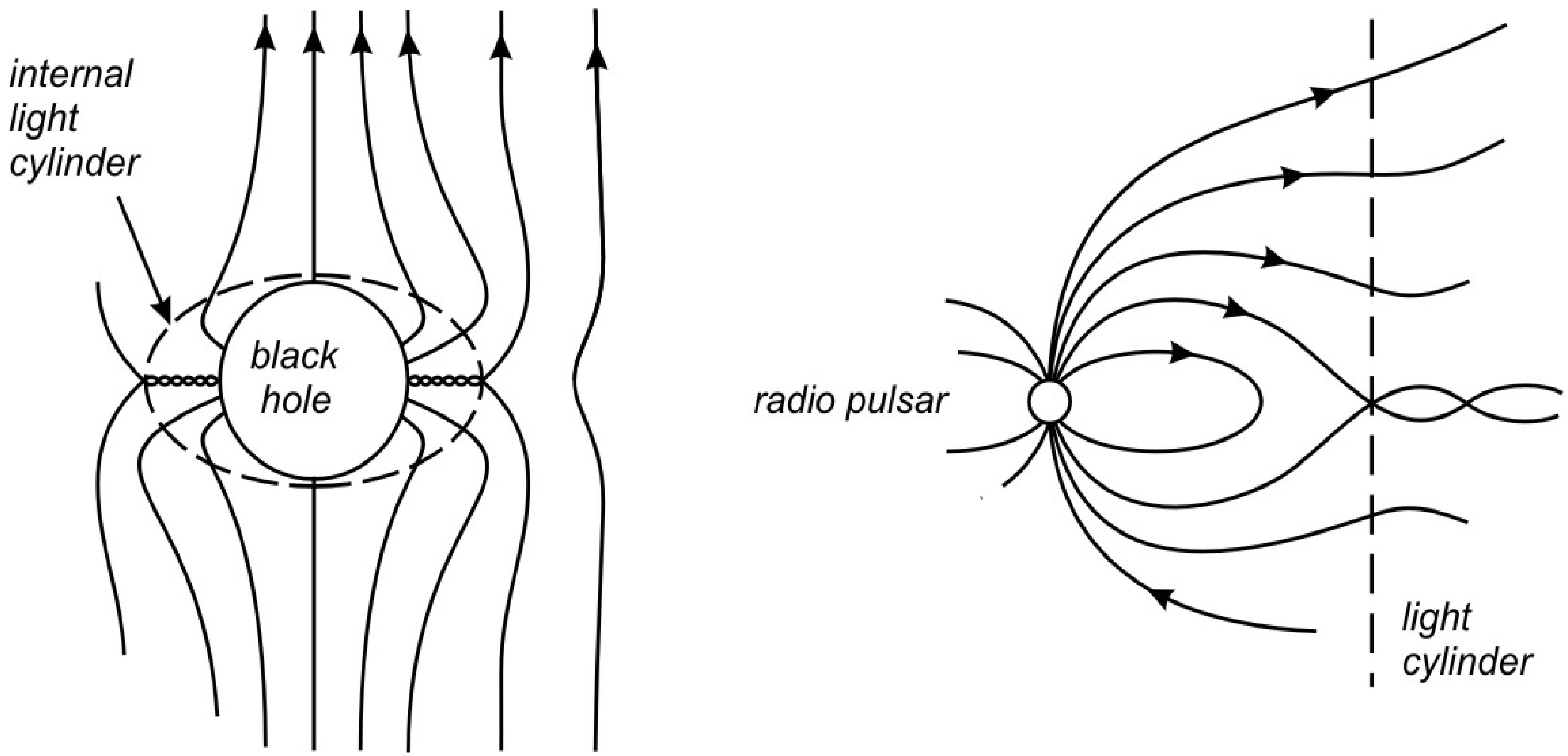
$$F=\frac{64\pi^4}{\mathbf{M}^4}\frac{K}{A^2}-\frac{64\pi^4}{\mathbf{M}^4}\alpha^2\varpi^2\eta^2\mu^2.$$

The answer (2)

- Longitudinal current is determined by the critical condition on the fast magnetosonic surface located outside the horizon.
- For this reason the conditions on the horizon cannot affect the energy loss.

Black hole magnetosphere

For the magnetosphere filled with plasma all the magnetic flux crossing the internal light surface, intersects the horizon as well



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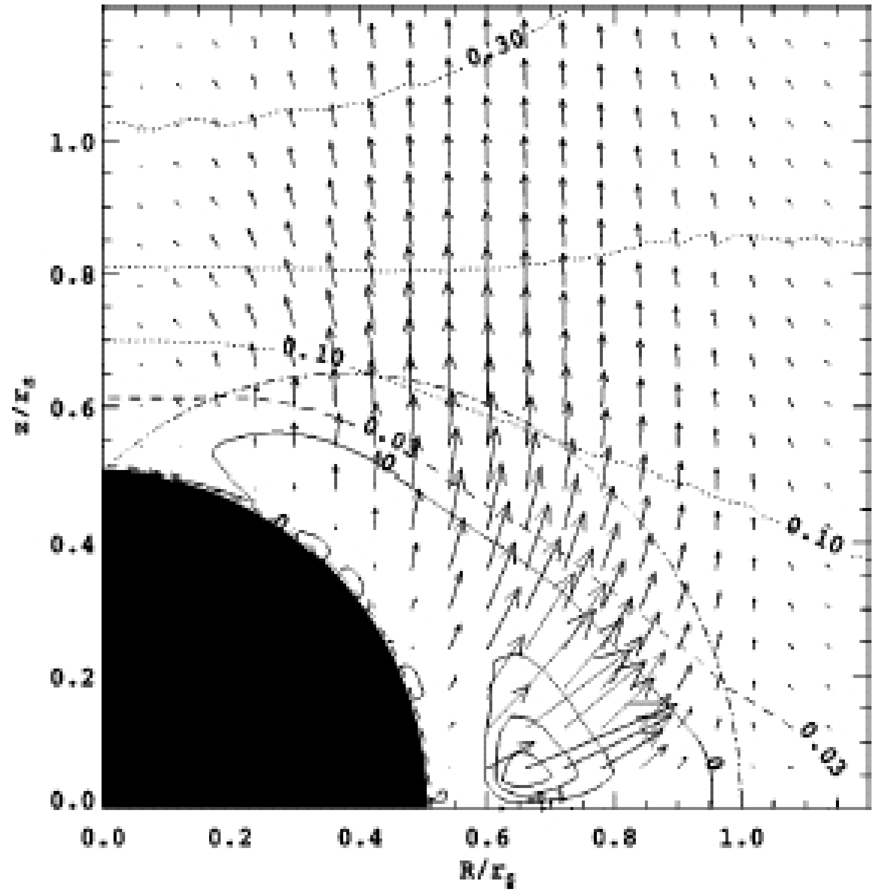

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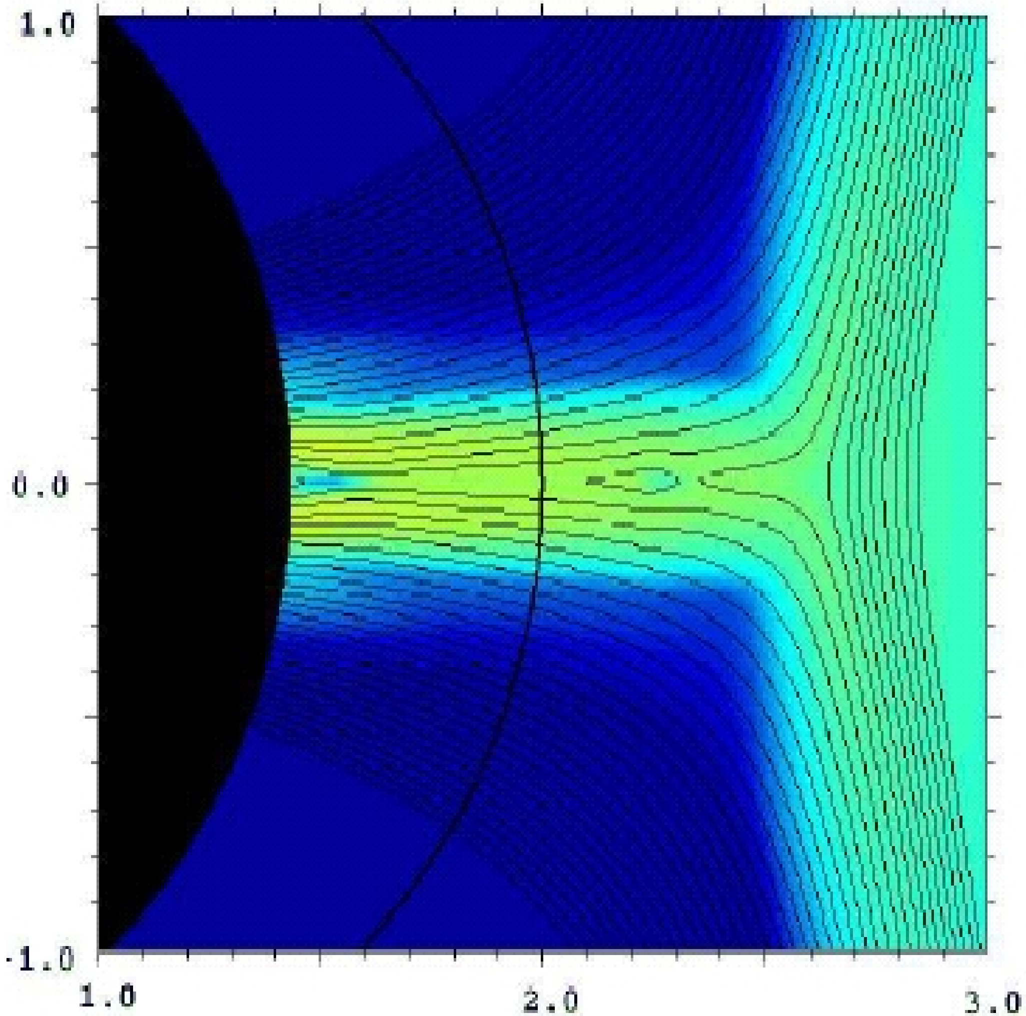

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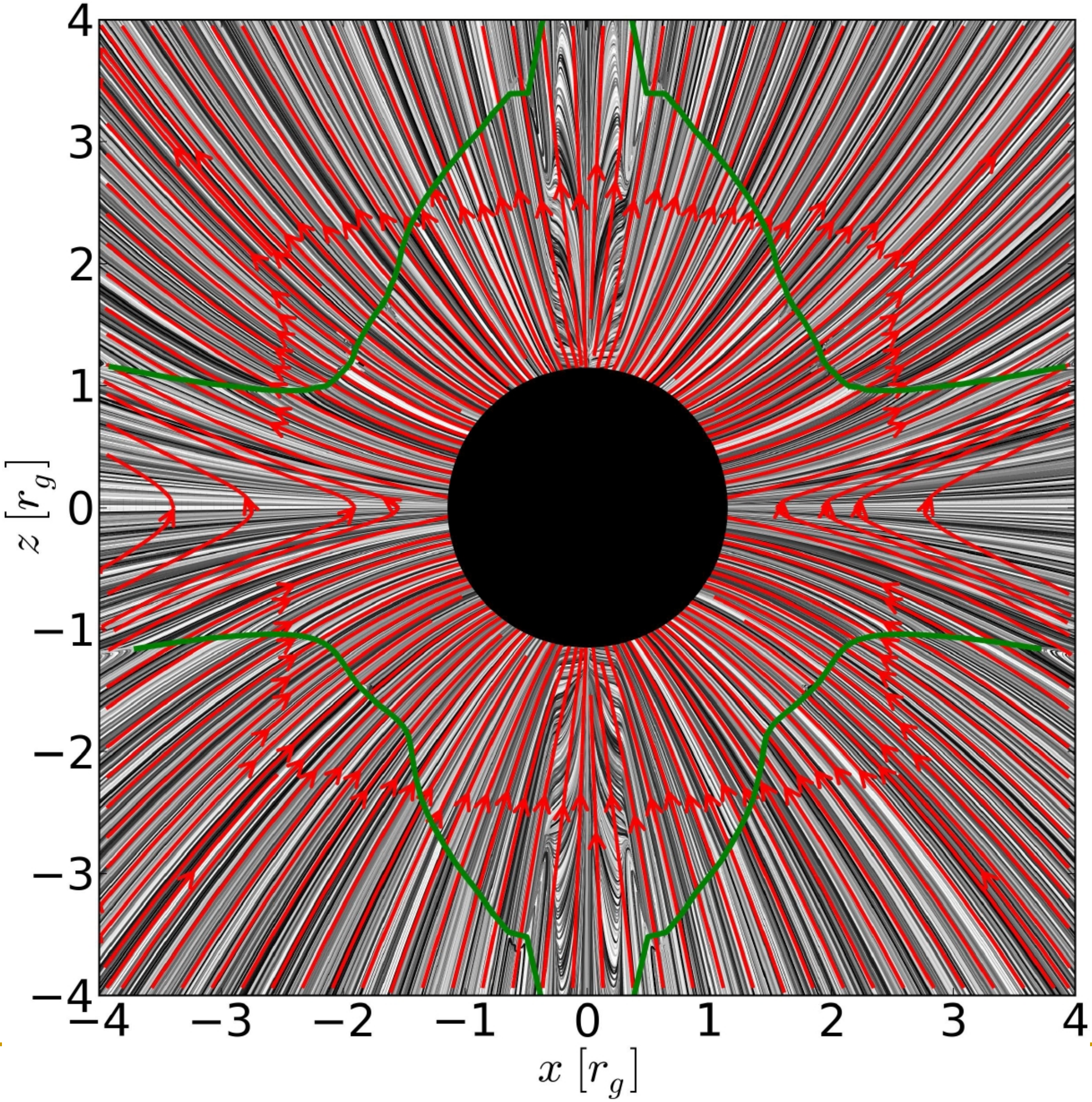

Conclusion

Rotating black hole submerged into the external magnetic field can lose its rotating energy by electric currents flowing in the magnetosphere.

Conclusion

The mechanism of the black hole braking differs from that of radio pulsars.

- It doesn’t result from surface currents flowing along black hole horizon.
- EMF results from frame dragging (Lense-Thirring effect) over the horizon, not from exterior forces inside the black hole.

Conclusion

The mechanism of the black hole braking differs from that of radio pulsars.

- Electric current fixed the energy loss does not depend on the “conductivity of the horizon”. It is determined y the critical condition on the fast magnetosonic surface located over the event horizon.