Jeturi produse de catre gaurile negre aflate in centrul galaxiilor

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SUMAR

- Galaxii cu nucleu activ: Ce vedem ? De ce vedem ?
- Posibile scenarii pentru formarea jeturilor
- Jeturi simulate numeric cu GRMHD (General Relativistic Magnetohydrodynamics)

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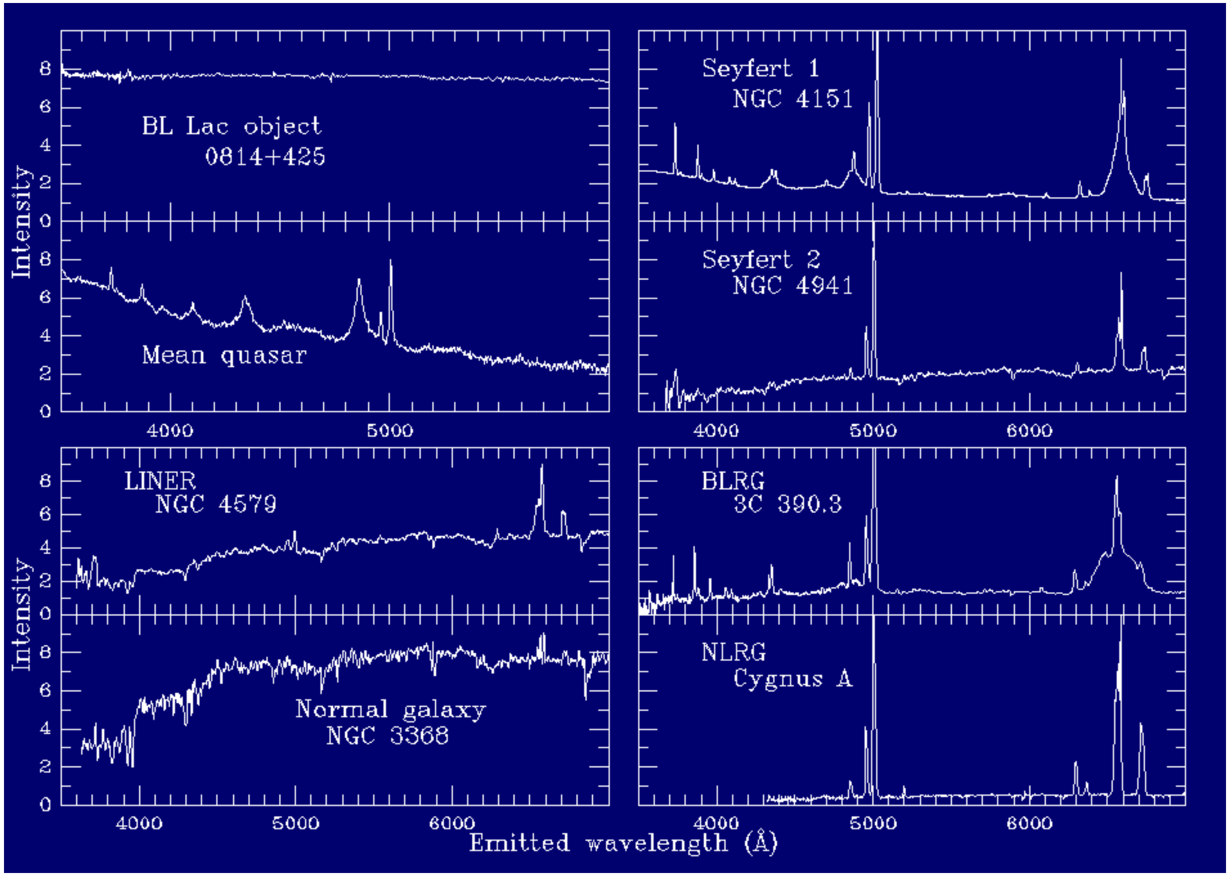
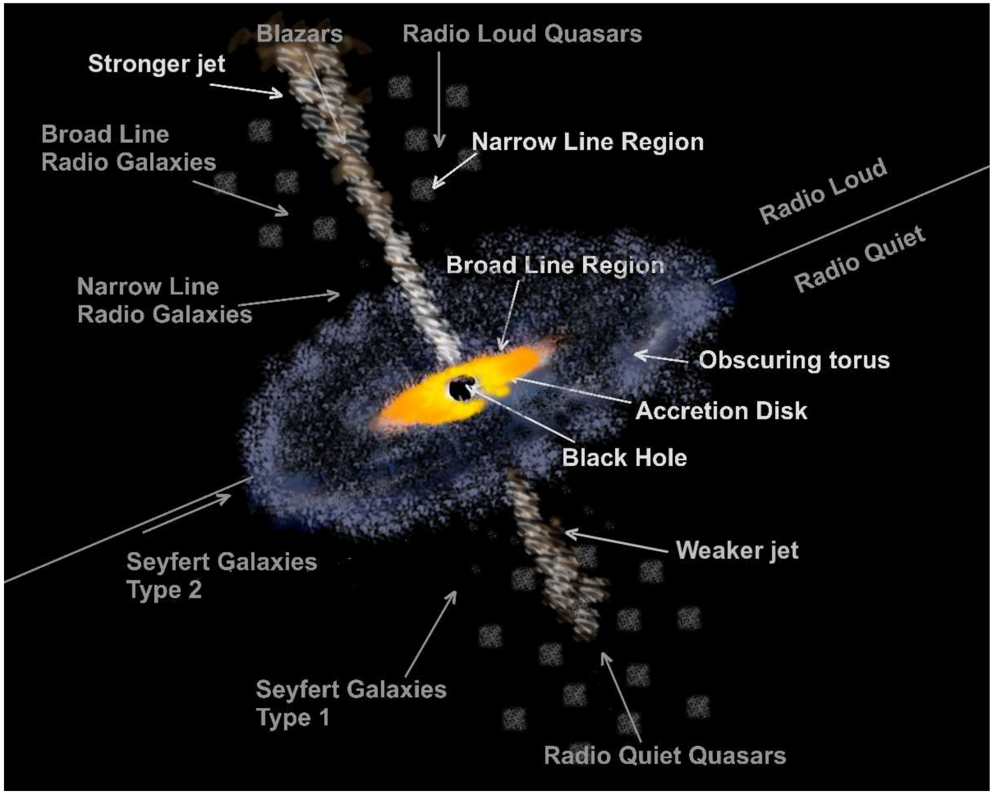
CE VEDEM ? DE CE VEDEM ?

Spectrele galaxiilor cu nucleu activ



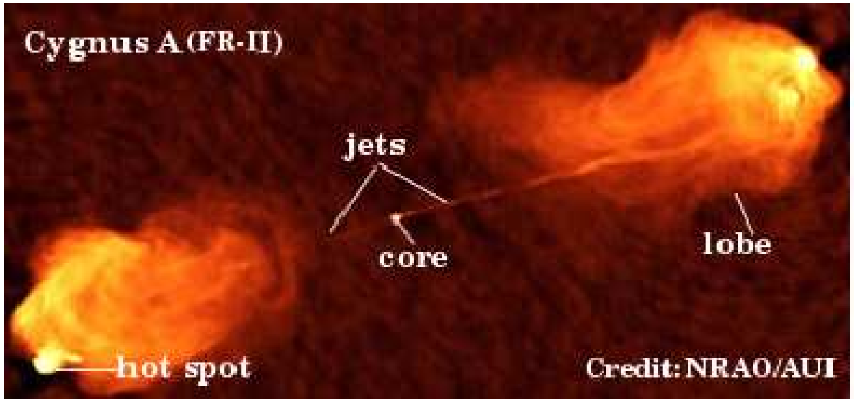
- AGN = galaxii ale caror nuclee nu pot fi explicate prin fizica stelara standard: un cluster masiv si dens de stele sau o gaura neagra de masa stelara

AGN



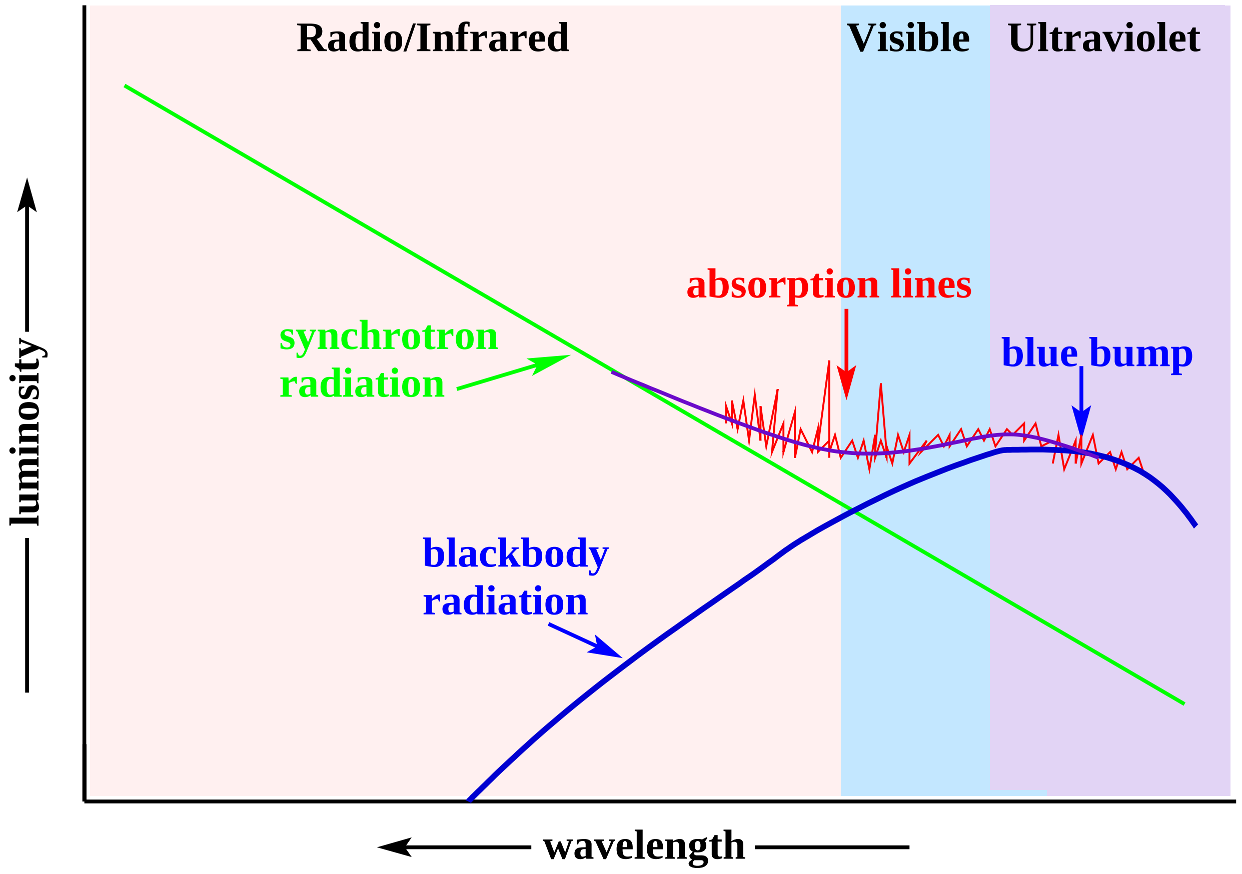
- gaura neagra supermasiva ($M \sim 10^7 - 10^9 M_\odot$) rotativa, inconjurata de un disc de accretie

- jeturile AGN: $v_{\rm jets} \sim 0.9 - 0.995c$ or $\gamma = 2 - 10$ (bulk Lorentz factor)



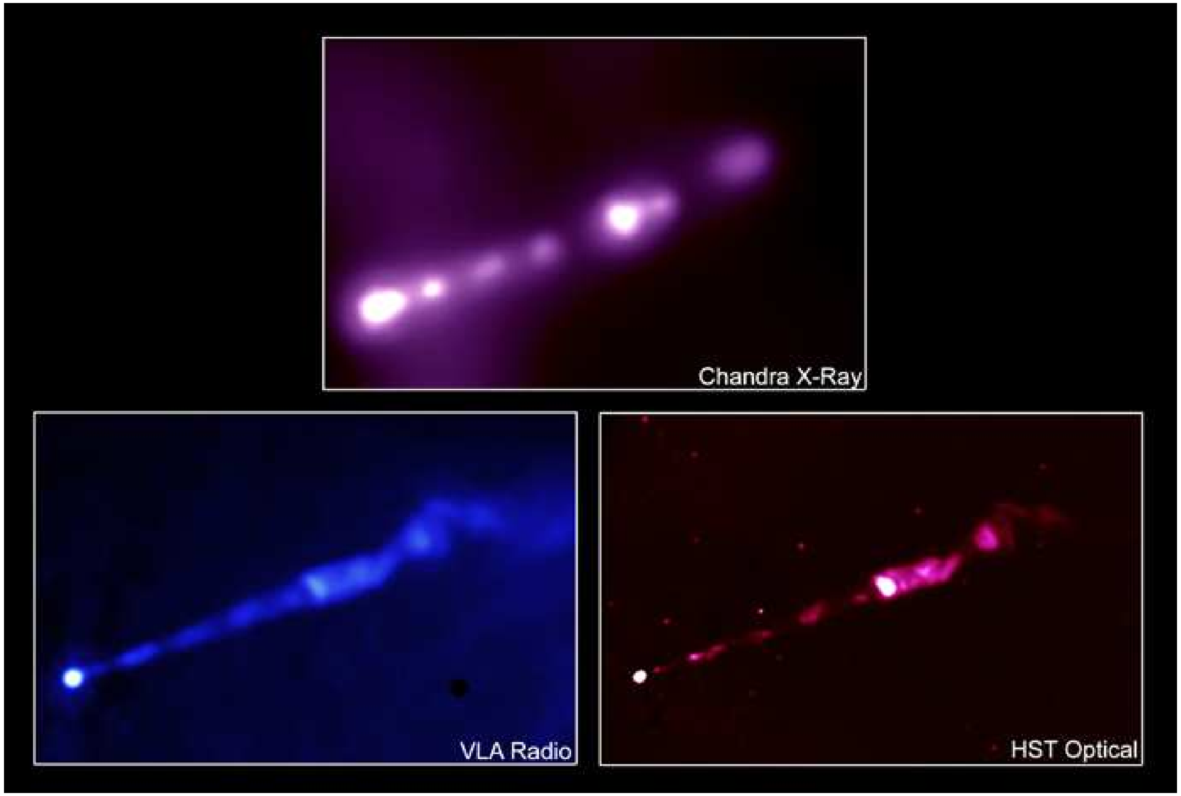
Credit: NRAO/AUI

AGN

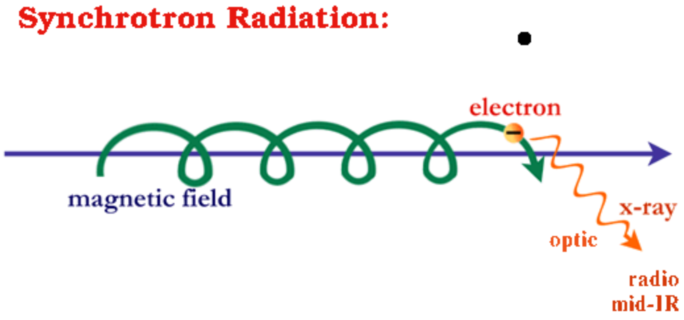


- power-law (non-thermal) radiation ($\nu^{-\alpha}$): jets
- blackbody (thermal) radiation: accretion disk

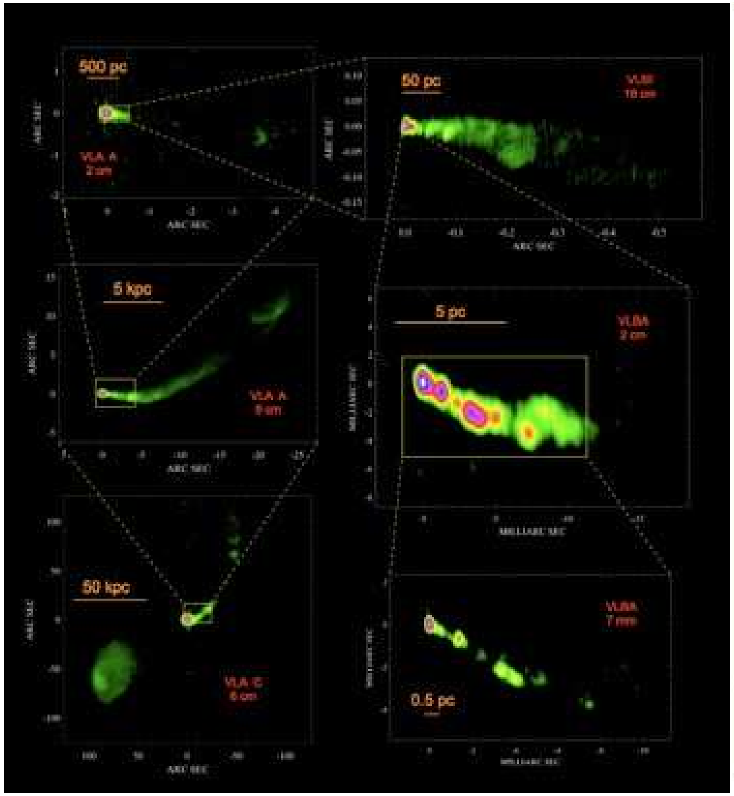
Radiatia de sincrotron in jeturile AGN

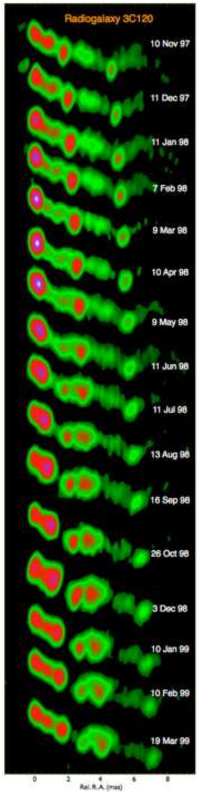


- emisie de radiatie de sincrotron pe tot spectrul de continuu



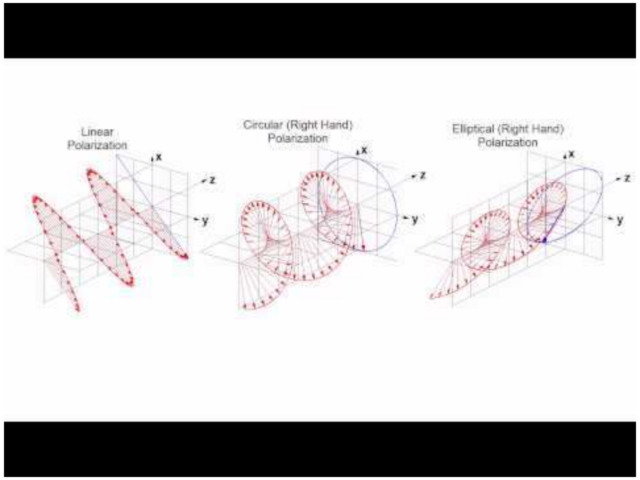
Radiatia de sincrotron in jeturile AGN





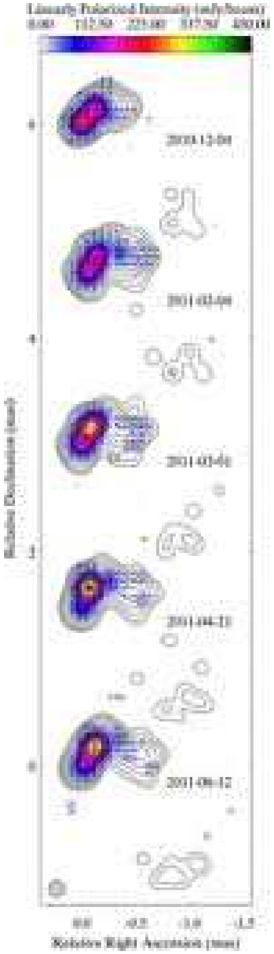
- rezolutie mai buna cu VLBI (Very Long Base Interferometry); lungimi de unda mai mici
- corelator: interferenta undelor coerente de la statiile VLBI

Polarizarea radiatiei in jeturile AGN



- “cartografierea” campului magnetic in jeturi

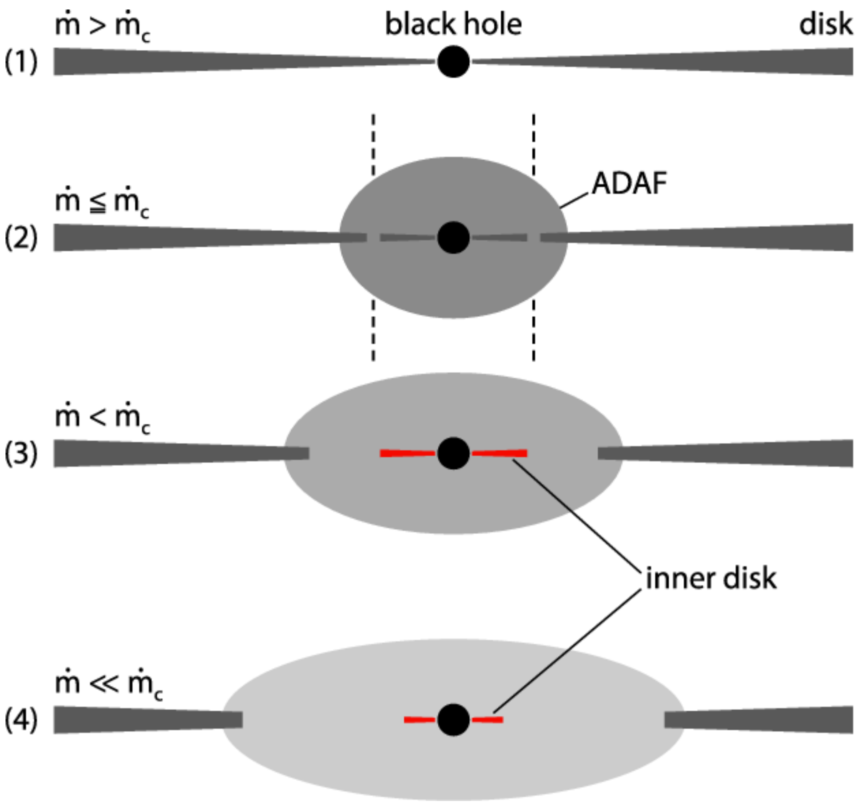
- vectorii camp electric sunt rotiti cu 90°



Tipuri de disc de acretie

- geometrically thin, optically thick disk reaching inward to the last stable orbit (for accretion rates between a few percent up to almost the Eddington rate)

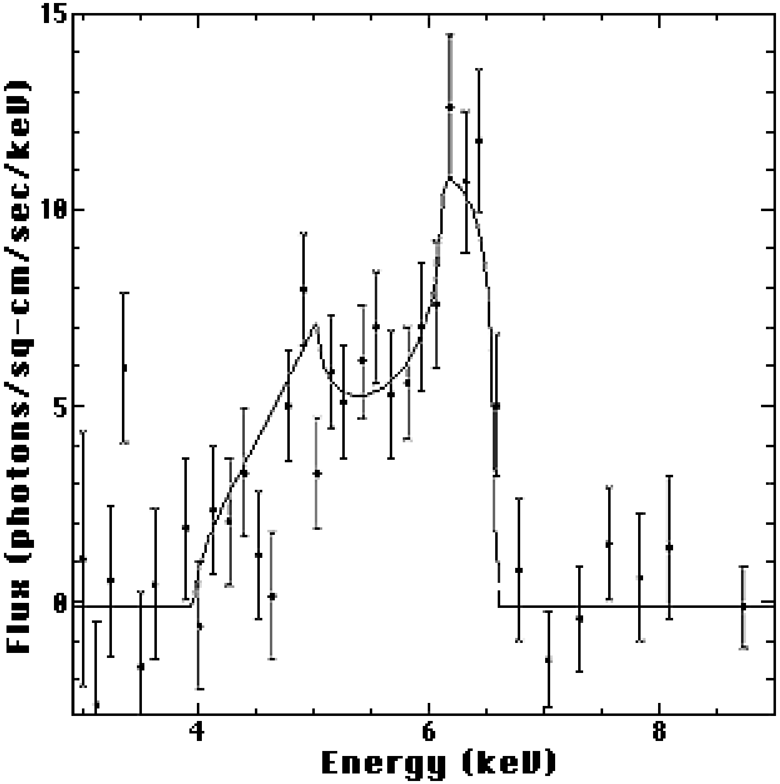
- hot optically thin, geometrically extended advection-dominated flow (ADAF)



- accretion rate: $\dot{m} = \frac{dm}{dt}$; luminosity: $L = \dot{m}c^2$

Linia Fe pentru discul de acretie

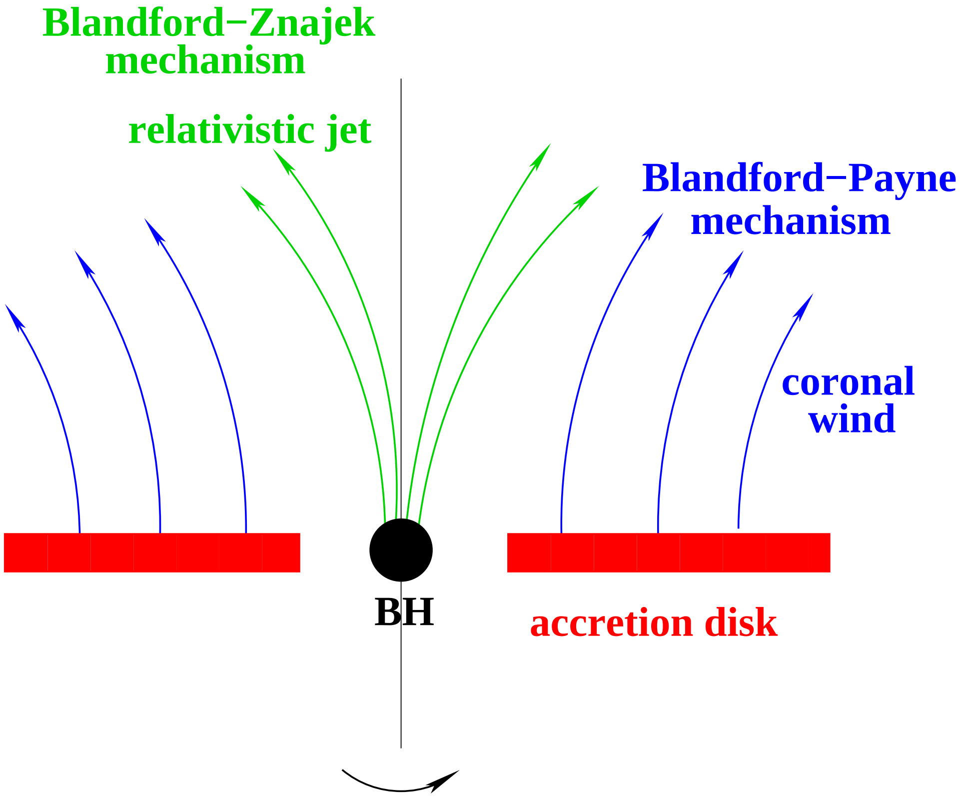
- Fe line: characteristic double-horned shape (Doppler effect)
- X-ray photons coming from close to the BH are gravitationally redshifted, introducing a characteristic distortion of the line
- gives an estimation for the BH mass (e.g., min 0.5 for Sgr A^*)

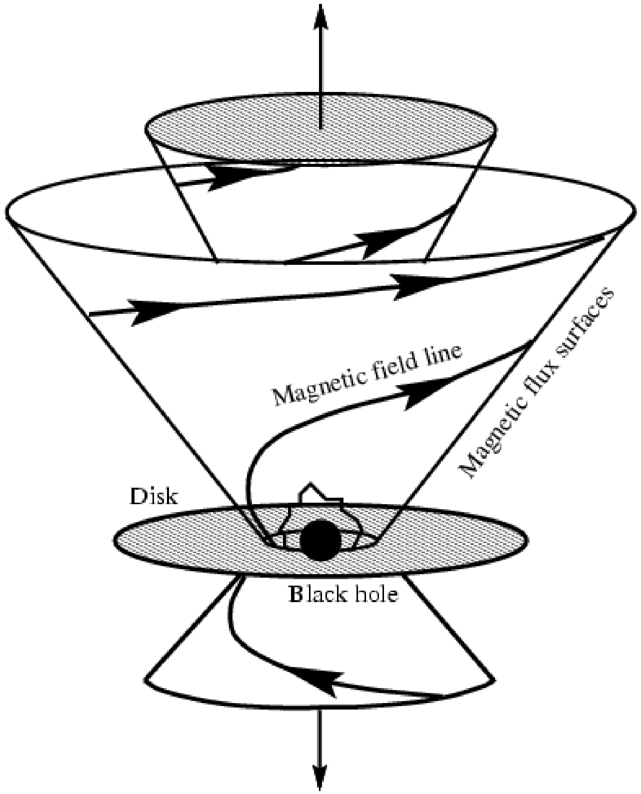


POSIBILE SCENARII PENTRU FORMAREA JETURILOR

Blandford-Payne mechanism

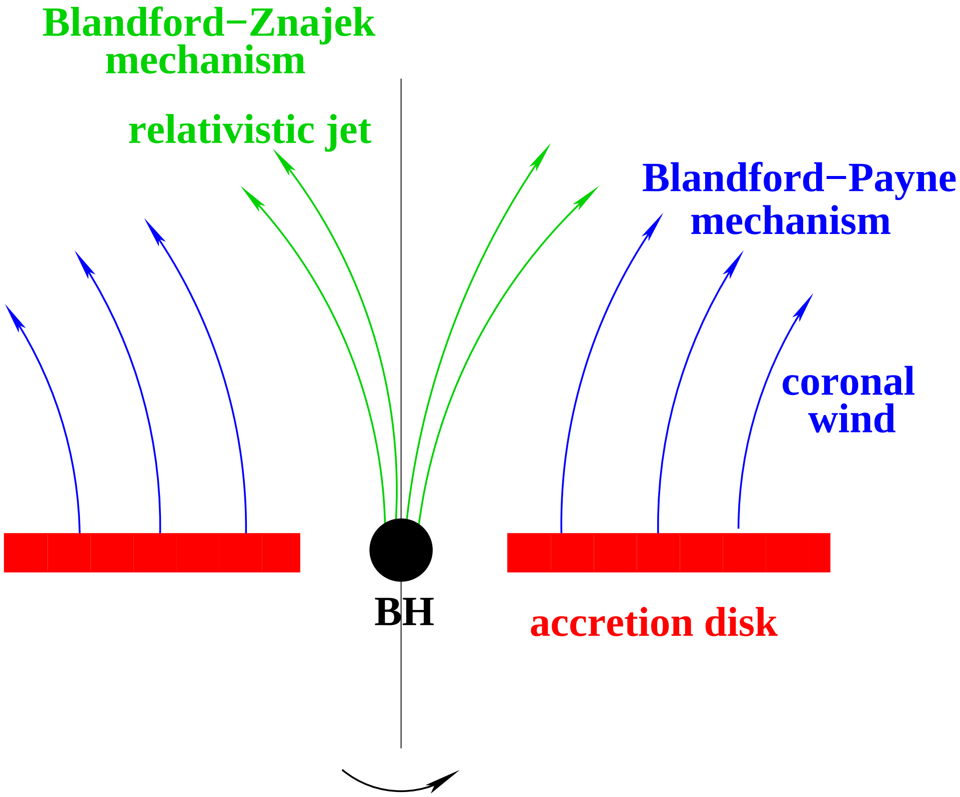
- Blandford-Payne mechanism (1982): MHD flow – the jet can be launched and collimated by centrifugal and magnetic forces – the disk particles are driven upwards by the gradient of the pressure in the disk to fill the corona around the disk and are further accelerated by the gradient of the magnetic pressure

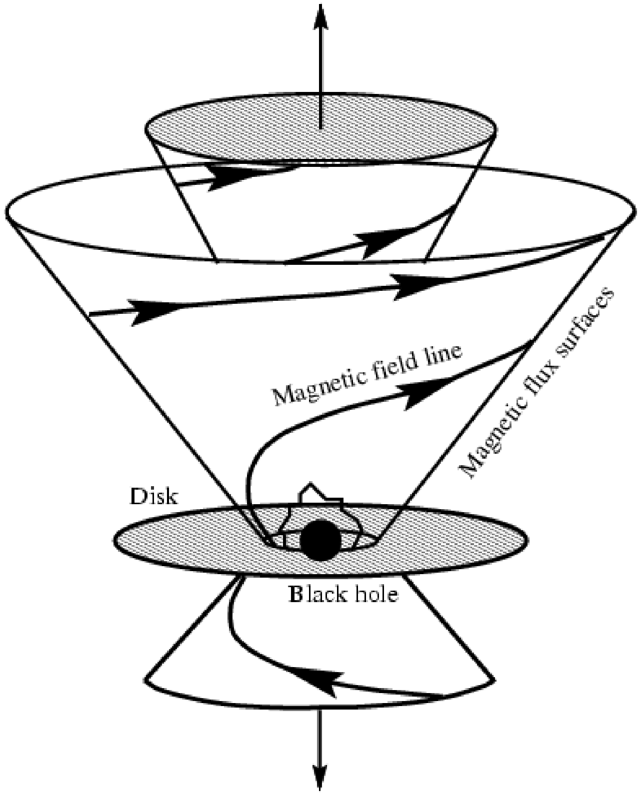




Blandford-Znajek mechanism

- Blandford-Znajek mechanism (1977): electromagnetically extraction of energy and angular momentum of a BH ("BH dynamo" mechanism) → the energy flux of the jets is provided by conversion of the BH rotational energy into Poynting flux, which is then dissipated at large distances from the BH by current instabilities





JETURI SIMULATE NUMERIC CU GRMHD

Kerr Black Holes

- Kerr space-time symmetries, Killing vectors: $\xi_t = (\partial_t), \xi_\phi = (\partial_\phi)$
- Kerr (1963) metric in Boyer-Lindquist (1967) coordinates (t,r,θ,ϕ):

$$ds^2 = -\left(1 - \frac{2Mr}{\Sigma}\right) dt^2 - \frac{4Mar\sin^2\theta}{\Sigma} dt\,d\phi + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{2Ma^2 r\sin^2\theta}{\Sigma}\right) \sin^2\theta\, d\phi^2$$

geometrical functions: $\Delta = r^2 - 2Mr + a^2$, $\Sigma = r^2 + a^2\cos^2$

$a = J/(Mc)$, BH spin

- energy-momentum tensor: $T_{\mu\nu}$
- conservation laws of energy, $\mathbf{E} \equiv \mathbf{T} \cdot \partial/\partial t$, and of angular momentum, $\mathbf{J} \equiv \mathbf{T} \cdot \partial/\partial\phi$

Kerr Black Holes

- event horizon = singularity of the BL coordinates, $\Delta = 0$:

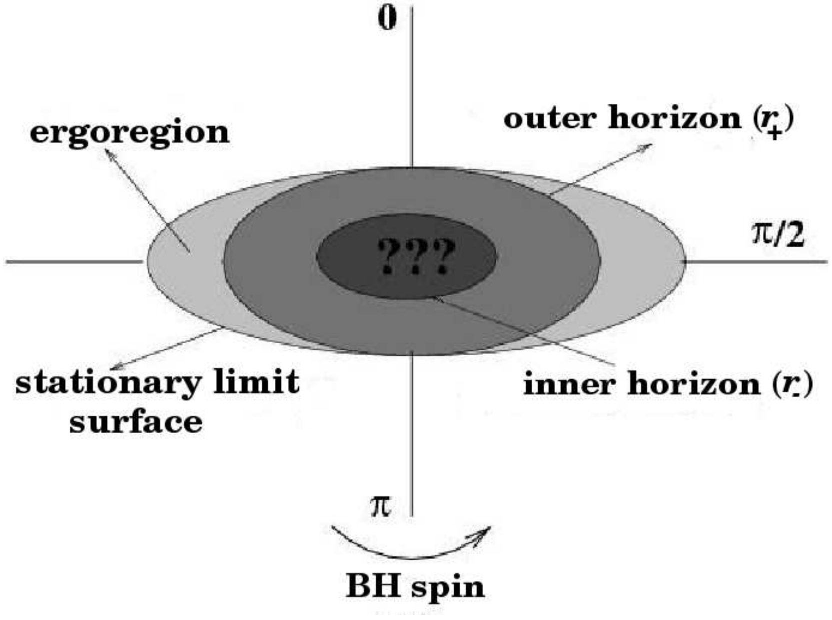
$$r_\pm = M \pm \sqrt{M^2 - a^2} = r_\mathrm{g}(1 \pm \sqrt{1 - a_*}),\ r_\mathrm{g} = GM/c^2 \text{ gravit. radius}$$

$$a_* = a/r_\mathrm{g},\ \boxed{-1 \leqslant a_* \leqslant 1},\ \text{BH spin parameter}$$

- ergosphere (stationary limit surface): time-like Killing vector becomes null

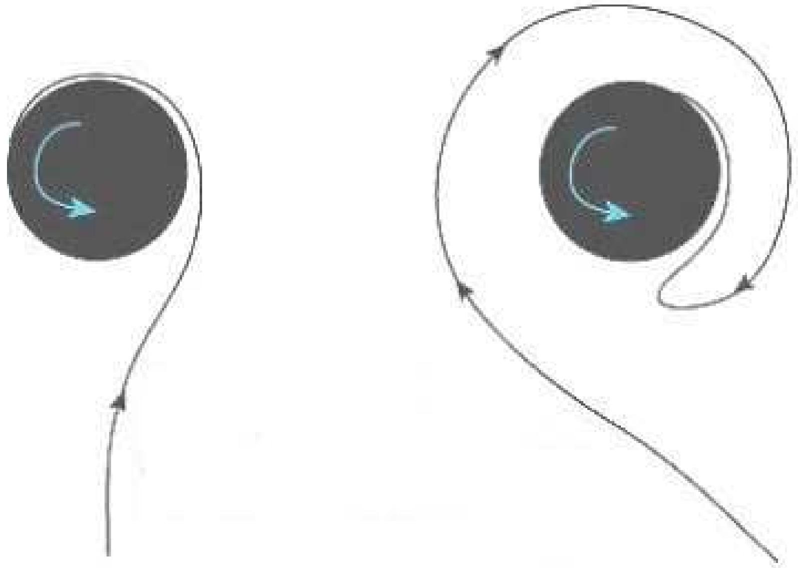
$$\xi_t \cdot \xi_t = g_{tt} = 0$$

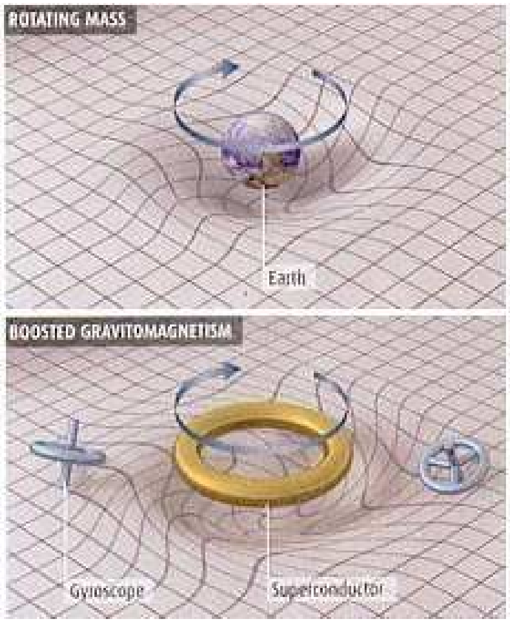
$$(r_\mathrm{sl})_{\theta=\pi/2} = 2\,r_\mathrm{g}$$



Kerr Black Holes

- frame-dragging effect: nothing inside the ergosphere can remain at rest with respect to distant observers, it must co-rotate with the BH rotation





Codul lui Koide et al.

SUMAR
CE VEDEM? DE CE?
FORMAREA JETURILOR
JETURI GRMHD
Kerr BHs
Codul Koide
Conditii initiale
Rezultate
Concluzii

- First GRMHD code for simulating jet formation from accreting BHs was developed by Koide et al. (1999) using the conservation form of the ideal GRMHD equations on fixed geometry (either Schwarzschild or Kerr)

- We use their code to simulate jet formation from a rapidly-spinning BH ($a_* = 0.95$), when the accretion disk co-rotates with the BH rotation and the coronal plasma falls freely towards the BH

- Main result: an electromagnetically-driven component of the jet which, near the BH, is developed inside the jet gas-pressure-driven component

- This is different from the previous results obtained by Koide et al., where the jet has two separately components (the pressure-driven and magnetically-driven components)

Codul lui Koide et al.

- GRMHD equations are written using the 3+1 decomposition of the space-time, where the coordinate time is split from the three spatial coordinates
- 4-D energy-momentum tensor: $T^{\mu\nu} = T^{\mu\nu}_{\text{fluid}} + T^{\mu\nu}_{\text{EM}}$ $(\mu, \nu = 0, \ldots, 3)$
- Ideal MHD: the fluid is considered to be a perfect conductor (of infinite conductivity)
- GRMHD equations form a set of 8 non-linear hyperbolic partial differential eqs.: conservation of rest mass, conservation of energy and momentum, and evolution of magnetic field (Maxwell's induction equation)
- Plus fluid's equation of state and $\nabla \cdot \mathbf{B} = 0$ condition
- Koide et al. solved the system of GRMHD equations: two-step Lax-Wendroff scheme with a total-variation- diminishing (TVD) diffusion term (Davis 1984)

Codul lui Koide et al.

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FORMAREA JETURILOR

JETURI GRMHD

- Kerr BHs
- Codul Koide
- Conditii initiale
- Rezultate
- Concluzii

In a compact form, the evolution equations of GRMHD can be written as

$$\boxed{\frac{1}{\sqrt{|g|}}\frac{\partial(\sqrt{\gamma}\mathbf{U})}{\partial t}+\frac{1}{\sqrt{|g|}}\frac{\partial(\sqrt{|g|}\,\mathbf{F})}{\partial x^i}=\mathbf{S}},$$

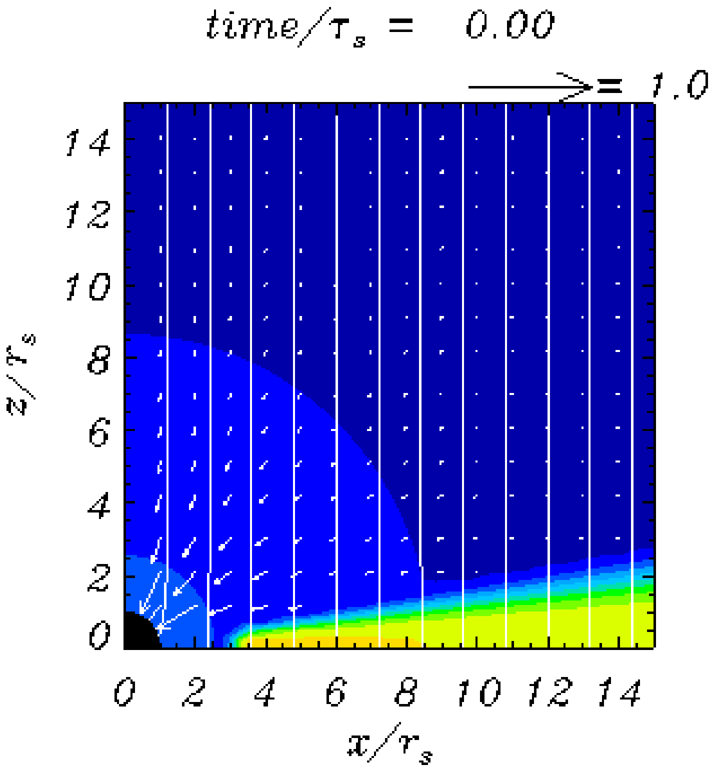
where the quantities **U** (conserved variables), **F** (fluxes), and **S** (source terms) are

$$\mathbf{U}=\begin{bmatrix} D \\ S_j \\ \tau \\ B^i \end{bmatrix}, \qquad \mathbf{F}=\begin{bmatrix} D\tilde{v}^i \\ T^i_j \\ \alpha T^{ti}-D\tilde{v}^i \\ \tilde{v}^i B^j-\tilde{v}^j B^i \end{bmatrix},$$

$$\mathbf{S}=\begin{bmatrix} 0 \\ T^{\mu\nu}\left(\frac{\partial g_{\nu j}}{\partial x^\mu}-\Gamma^\sigma_{\nu\mu}g_{\sigma j}\right) \\ \alpha\left(T^{\mu t}\frac{\partial \ln\alpha}{\partial x^\mu}-T^{\mu\nu}\Gamma^t_{\nu\mu}\right) \\ 0^i \end{bmatrix}.$$

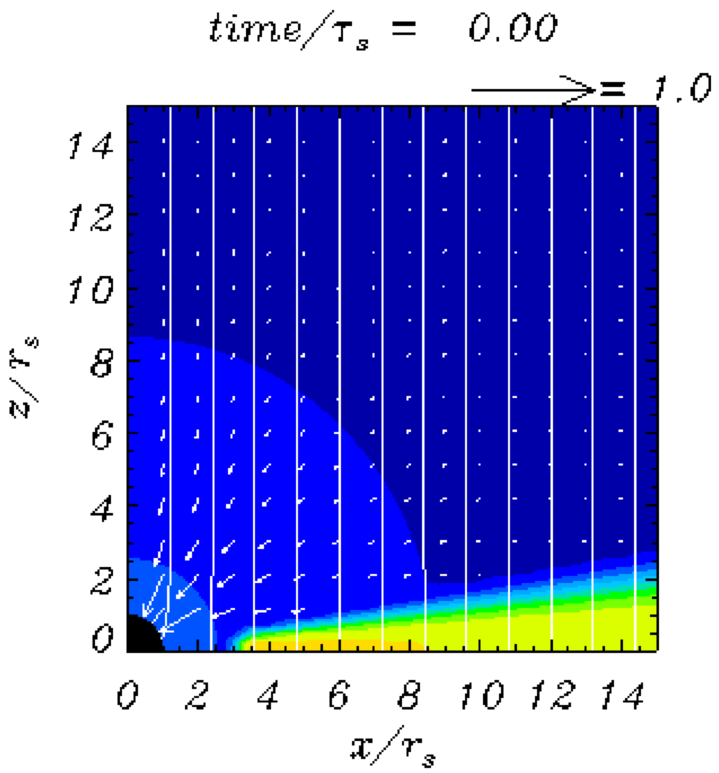
Conditii initiale

- 2.5-D simulations in the numerical domain $1.5 r_S \leqslant R \leqslant 15 r_S$, $0 \leqslant \theta \leqslant \pi/2$ with 128×128 grid points ($r_S = 2MG/c^2$)
- Numerical computation is scale free (i.e., physical quantities do not depend on the BH mass)
- BH spin parameter: $a_* = 0.95$
- Uniform magnetic field (Wald solution 1974); set a weak field
- Coronal plasma: transonic free-fall flow



Conditii initiale

- Thin Keplerian disk co-rotates with the BH
- Disk inclination angle with respect to the BH equatorial plane is 15°
- Inner edge of the disk is at $r = 3r_S$
- Ratio of the disk mass density to the coronal mass density is 100



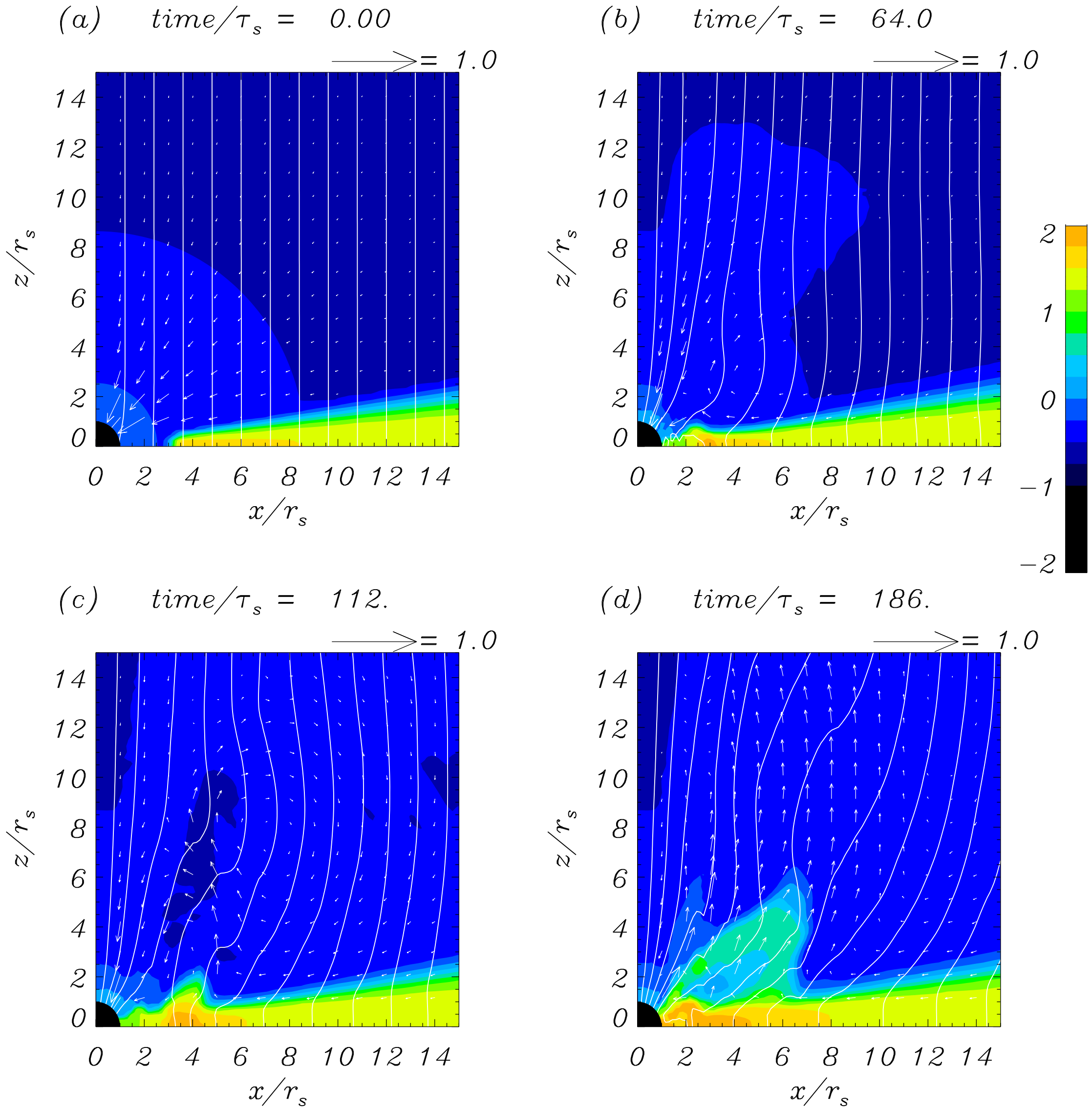
- Free boundary condition at the inner and outer boundaries is used (waves, fluids, and magnetic fields can pass through freely)

Rezultate

- Color = log(rest-mass density), Arrow = plasma poloidal velocity, Solid line = poloidal magnetic field line

- Gas pressure force & electromagnetic force

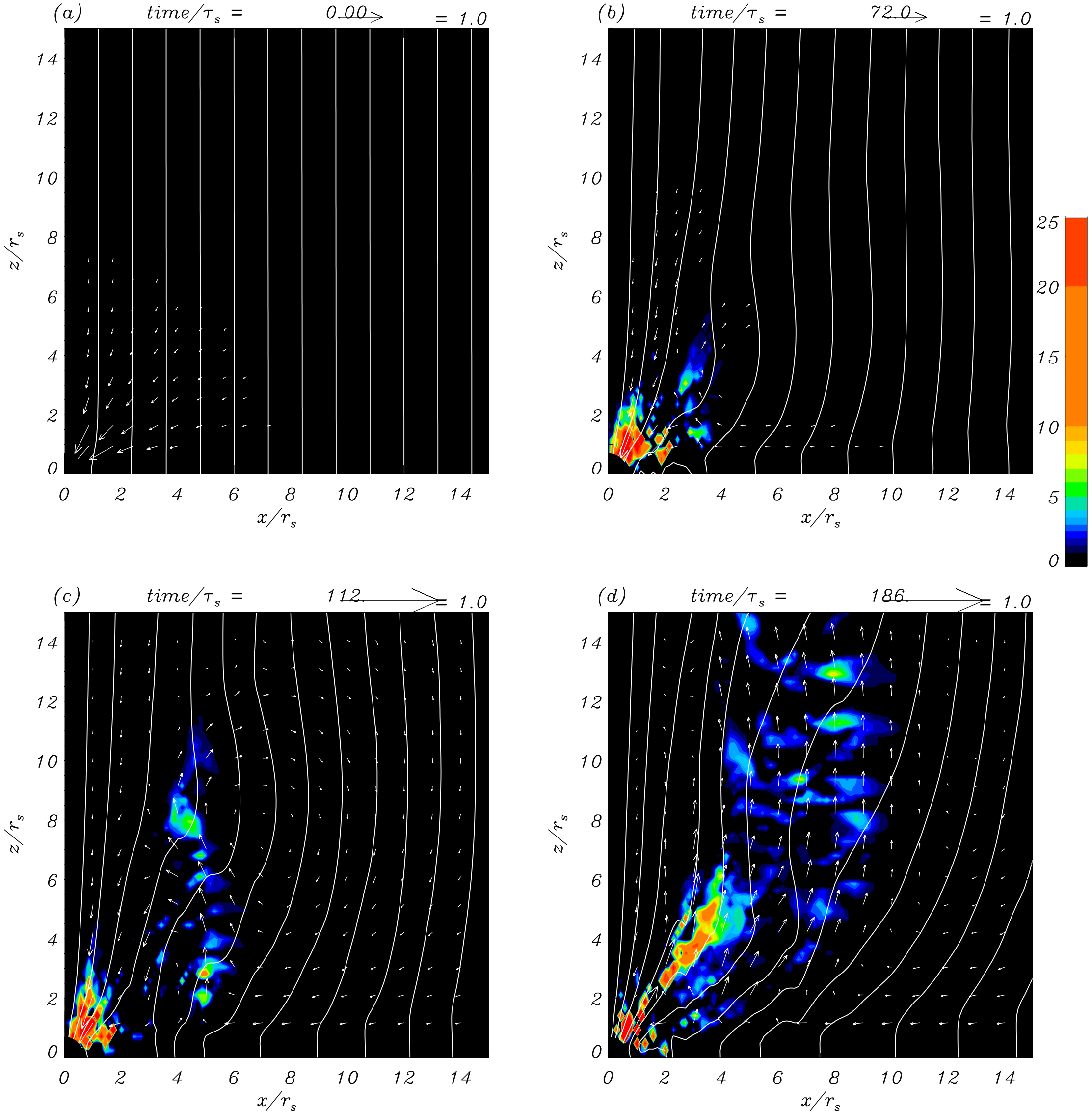
- Shock at $\sim 3r_S$ → gas pressure-driven component of the jet



Rezultate

Rezultate

- Color = magnitude of the electromagnetic force in the *z* direction that accelerates the plasma
- Magnetic field lines are twisted counter to the disk rotation
- Magnetically-driven component of the jet: twisting of the magnetic field and a Penrose-like process
- Jet is formed almost along the poloidal magnetic field lines
- Maximum total velocity of the jet is $\sim 0.4c$



Concluzii

- GRMHD simulation of jet formation from a thin accretion disk that co-rotates with a rapidly-spinning BH ($a_* = 0.95$) in a free-falling corona, using the code developed by Koide et al. (1998, 2000, 2003)
- Set the simulation parameters in such a way to perform a longer term simulation
- Electromagnetically-driven component of the jet is developed inside the gas pressure-driven component of the jet
- Similar to Koide et al., the maximum jet velocity obtained in this numerical simulation is $\sim 0.4c$