Radiative Penrose process:

energy gain by a single radiating charged particle in ergosphere of rotating black hole

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We demonstrate an extraordinary effect of energy gain by a single radiating charged particle inside the ergosphere of a Kerr black hole in presence of magnetic field. We solve numerically the covariant form of the Lorentz-Dirac equation reduced from the DeWitt-Brehme equation and analyze energy evolution of the radiating charged particle inside the ergosphere, where the energy of emitted radiation can be negative with respect to a distant observer in dependence on the relative orientation of the magnetic field, black hole spin and the direction of the charged particle motion. Consequently, the charged particle can leave the ergosphere with energy greater than initial in expense of black hole's rotational energy. In contrast to the original Penrose process and its various modification, the new process does not require the interactions (collisions or decay) with other particles and consequent restrictions on the relative velocities between fragments. We show that such a Radiative Penrose effect is potentially observable and discuss its possible relevance in formation of relativistic jets and in similar high-energy astrophysical settings.

• M. Kološ, A. Tursunov and Z. Stuchlík: *Radiative Penrose process: Energy Gain by a Single Radiating Charged Particle in the Ergosphere...*, submitted to PRD (2020) [arXiv:2010.09481]

Rotating black hole ergosphere

rotating BH - Kerr metric / geometric units ($G = 1 = c$)

$$ds^2 = g_{tt}dt^2 + 2g_{t\phi}dtd\phi + g_{\phi\phi}dr^2 + g_{rr}dr^2 + g_{\theta\theta}d\theta^2$$

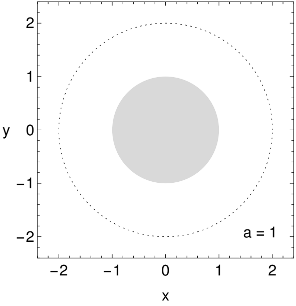
- BH event horizon r_H - $1/g_{rr} = 0$ boundary beyond which events cannot affect an observer

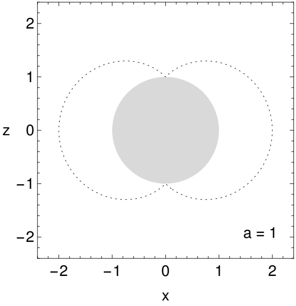
$$r_H = M + \sqrt{M^2 - a^2}$$

- BH ergosphere - g_{tt} changes sign from positive to negative - bounded by the surfaces:

$$r_H < r_{ergo} < M + \sqrt{M^2 - a^2 \cos^2\theta}.$$

In the ergosphere the energy of a test particle (photon) can become negative (related to infinity) allowing extraction of the BH's rotational energy.





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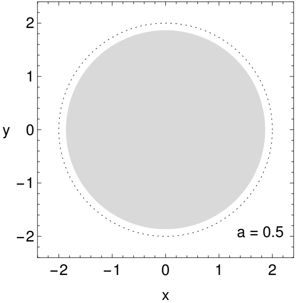
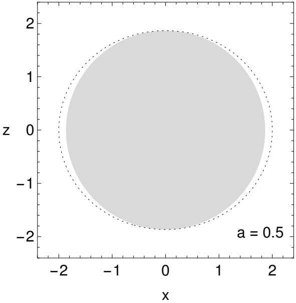




Electromagnetic field around black hole (BH magnetosphere)

in realistic astrophysical situations the magnetic field is test field (if $\ll\ 10^{18}$ Gs)
assumption: mag. field and matter around BH not contribute to spacetime curvature

Analytic solution to the vacuum Maxwell equations in Kerr spacetime

$$
\begin{aligned}
A_t &= \frac{B}{2}\left(g_{t\phi} + 2a g_{tt}\right) - \frac{Q}{2} g_{tt} - P\frac{a\cos\theta}{\Sigma^2} \\
A_\phi &= \frac{B}{2}\left(g_{\phi\phi} + 2a g_{t\phi}\right) - \frac{Q}{2} g_{t\phi} - P\frac{(r^2+a^2)\cos\theta}{\Sigma^2}
\end{aligned}
$$

where B, Q is magnitude of uniform magnetic field and electric charge from Wald solution and P magnetic monopole charge from Blandford & Znajek. We assume axial symmetry to the electromagnetic field configurations and components $A_r = A_\theta = 0$.

- Electric monopole $(B = 0, Q \neq 0, P = 0)$
- Magnetic monopole $(B = 0, Q = 0, P \neq 0)$
- Uniform mag. field $(B \neq 0, Q = 0, P = 0)$
- Uniform mag. field with Wald charge $(B \neq 0, Q = Q_{\mathrm{W}}, P = 0)$

Radiating charged particle dynamics in curved spacetime

radiation emitted by a charged particle leads to appearance of **back-reaction force**

$$\frac{\mathrm{d}u^\mu}{\mathrm{d}\tau} + \Gamma^\mu_{\alpha\beta} u^\alpha u^\beta = \frac{q}{m} F^\mu{}_\nu u^\nu + \frac{q}{m} \mathcal{F}^\mu{}_\nu u^\nu, \tag{1}$$

Lorentz force is given by EM tenzor $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$; back-reaction force $\frac{q}{m}\mathcal{F}^\mu{}_\nu u^\nu$

$$\begin{aligned}
\frac{du^x}{d\tau} &= \frac{qB}{m} u^y - \frac{2q^4B^2}{3m^3} \left(1 + u_\perp^2\right) u^x, \\
\frac{du^y}{d\tau} &= -\frac{qB}{m} u^x - \frac{2q^4B^2}{3m^3} \left(1 + u_\perp^2\right) u^y, \\
\frac{du^z}{d\tau} &= -\frac{2q^4B^2}{3m^3} u_\perp^2 u^z, \\
\frac{du^t}{d\tau} &= -\frac{2q^4B^2}{3m^3} u_\perp^2 u^t.
\end{aligned}$$

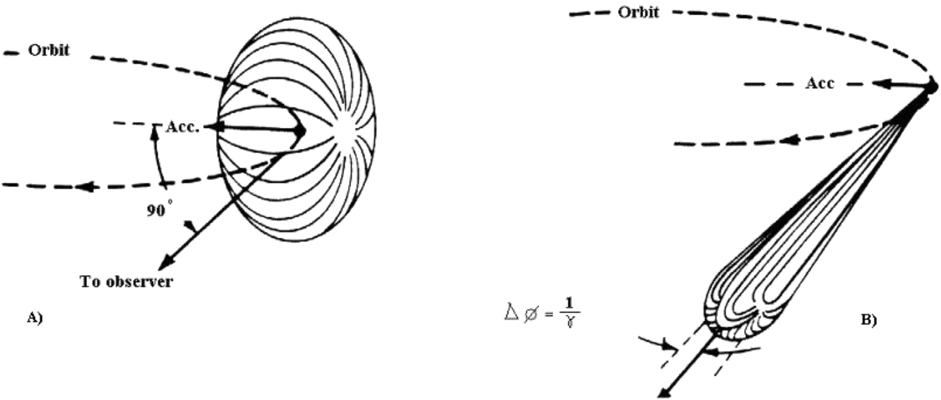
Magnetic field is strong: Lorentz force is relevant for any charged particle (e^- !!!), but radiation reaction can be relevant only for electrons.

BH mass	ISCO orbit	max.mag.field	e^- cooling
$10^1\ M_\odot$	10^{-3} s	$B \sim 10^8$ Gs	10^{-8} s
$10^9\ M_\odot$	10^{+4} s	$B \sim 10^4$ Gs	10^{+0} s

here $u_\perp^2 = (u^x)^2 + (u^y)^2$; e^- cooling - half energy lost due to radiation

- A. Tursunov, M. Kološ, Z. Stuchlík and D. V. Gal'tsov : *Radiation reaction of charged particles orbiting mag. Schw. BH*, The Astro. Journal 861 (1), 16 (2018) [arXiv:1803.09682]

Emitted synchrotron radiation



When the electron velocity approaches the speed of light, the emission pattern is sharply collimated forward - photon emission will slow down the radiating electron.

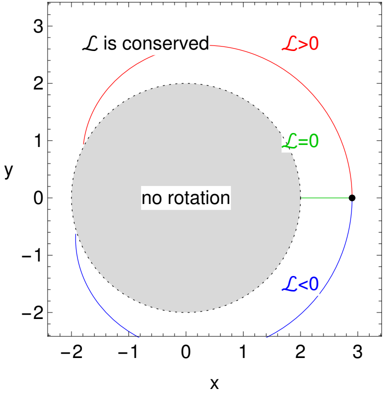
`https://en.wikipedia.org/wiki/Synchrotron_radiation`

Particles (photons) with negative energy

- frame draging (Lense–Thirring effect) inside the ergosphere everybody has to be co-rotating with the BH $u^\phi = \mathrm{d}\phi/\mathrm{d}t > 0$
- angular momentum $\mathcal{L} = u_\phi$ and particle energy $\mathcal{E} = -u_t$ are constant of the motion
- Locally Non Rotating Frames $\mathcal{L} = u_\phi = 0$
- contra-rotating (with respect to LNRF) particles (photons) can have negative energies

$$\mathcal{E} = -u_t < 0, \quad \mathcal{L} = u_\phi < 0$$

as seen by the asymptotic stationary observers



Can moving charged particle radiate photons with negative energies (as seen by the asymptotic stationary observers) in the rotating BH ergosphere? What will be consequences of negative photon emission on radiating charged particle dynamics?

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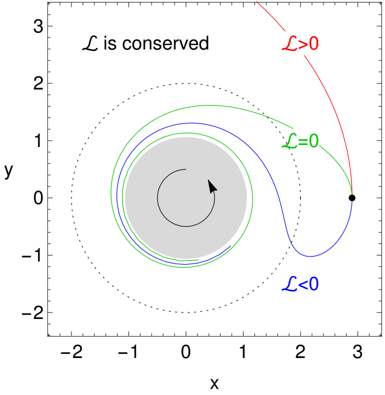

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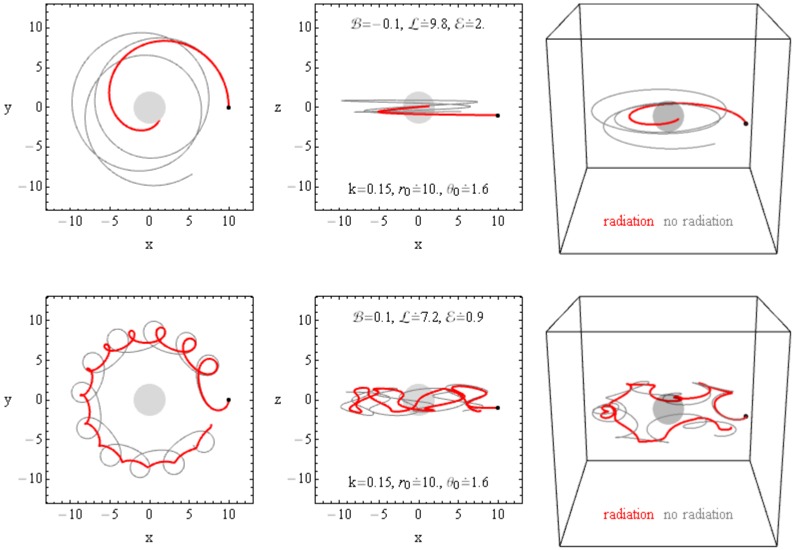
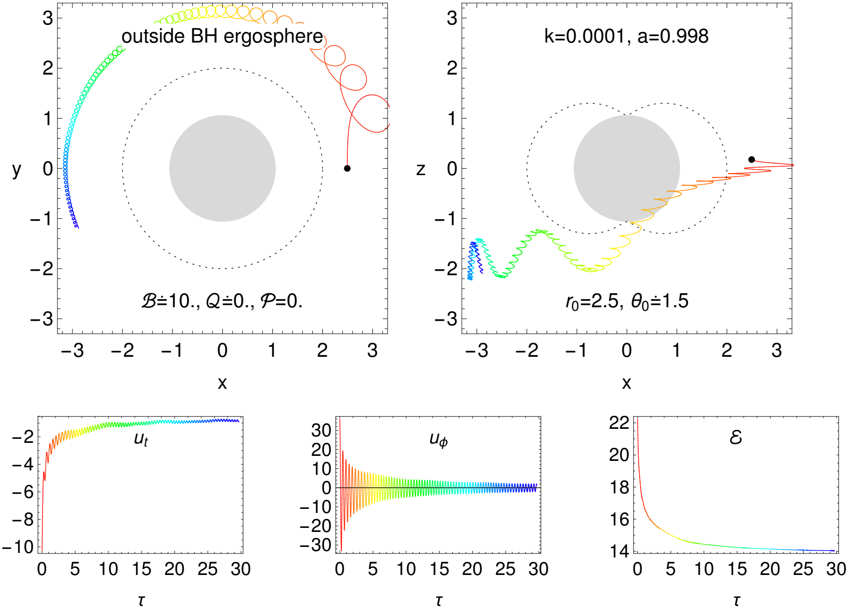
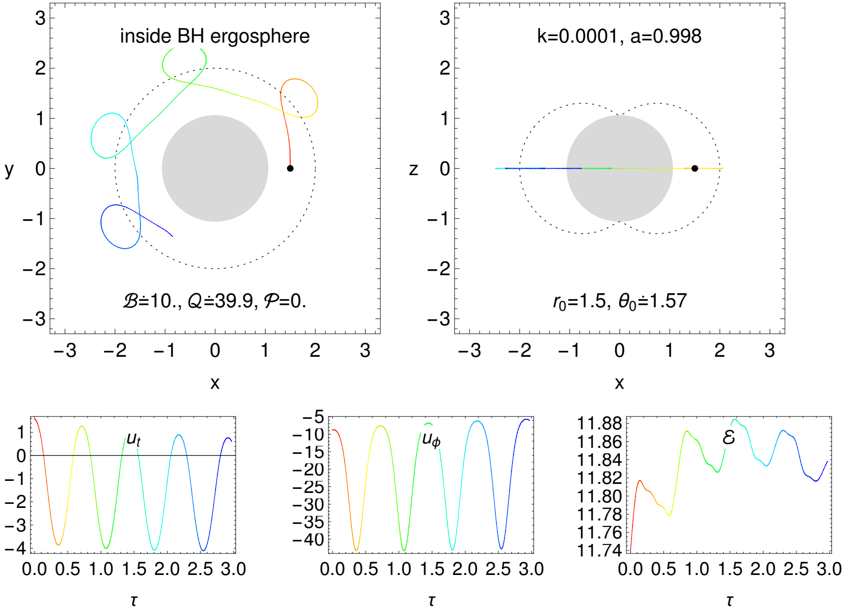
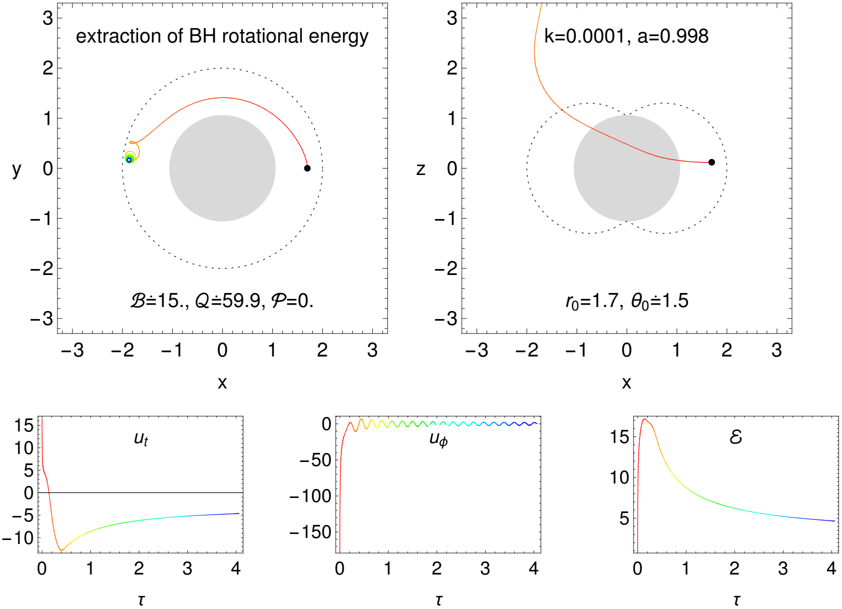
Effect of radiation reaction on charged particle trajectory

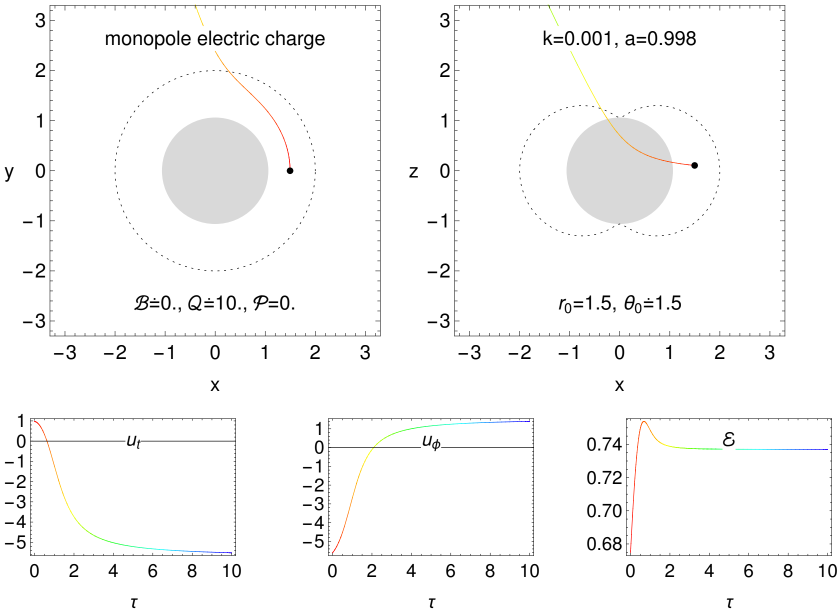




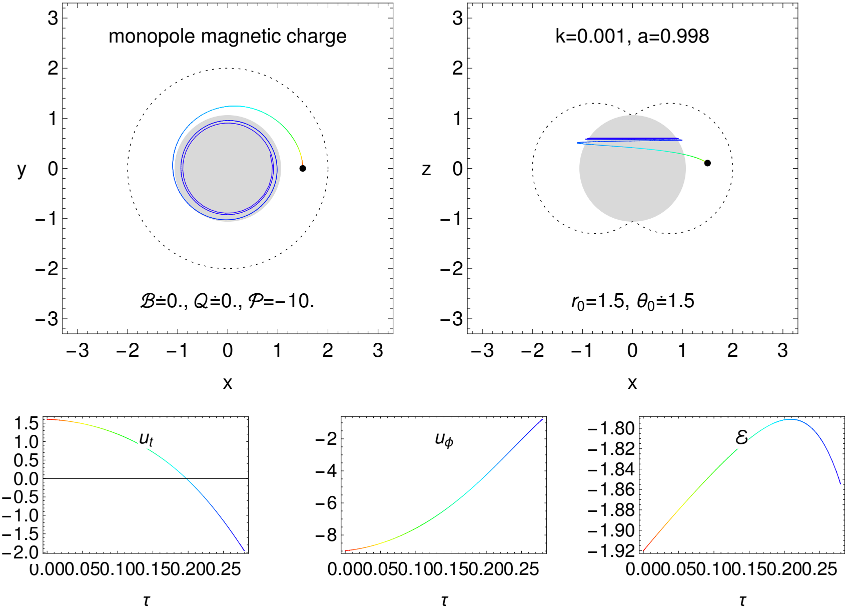
outside BH ergosphere
k=0.0001, a=0.998
$\mathcal{B}$≐10., $\mathcal{Q}$≐0., $\mathcal{P}$=0.
r_0=2.5, θ_0≐1.5
y
z
x
x
u_t
u_ϕ
$\mathcal{E}$
τ
τ
τ

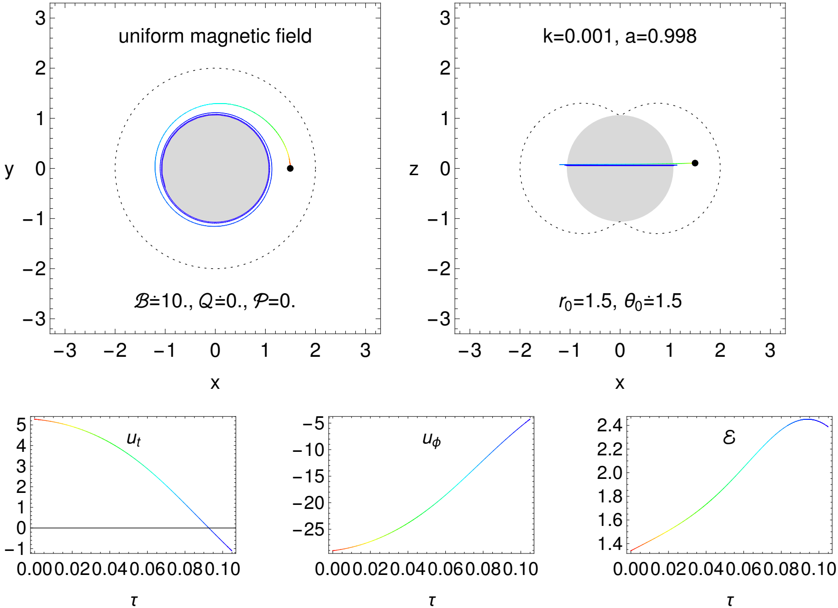

inside BH ergosphere
k=0.0001, a=0.998
$\mathcal{B}$≐10., $\mathcal{Q}$≐39.9, $\mathcal{P}$=0.
r_0=1.5, θ_0≐1.57
x
y
z
u_t
u_ϕ
$\mathcal{E}$
τ

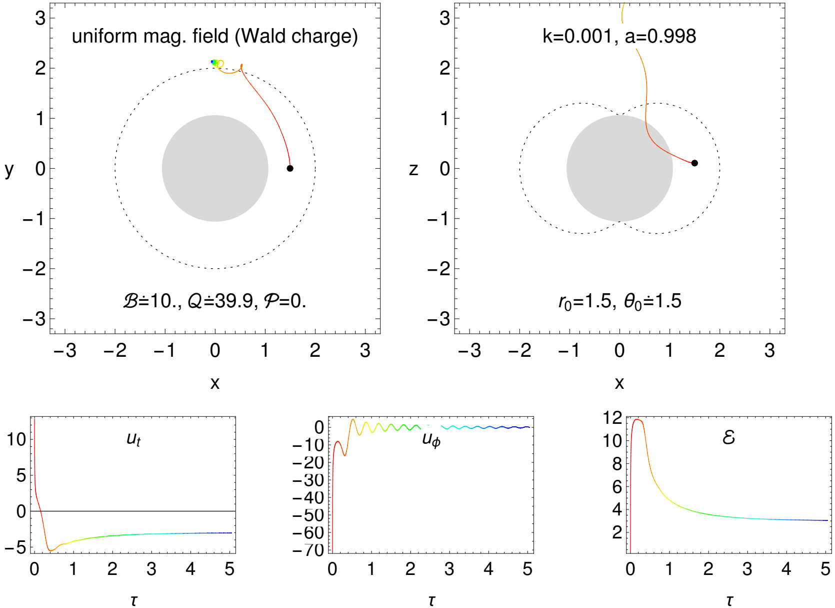

extraction of BH rotational energy
$\mathcal{B} \doteq 15., \mathcal{Q} \doteq 59.9, \mathcal{P}=0.$
k=0.0001, a=0.998
$r_0=1.7, \theta_0 \doteq 1.5$
x
y
z
u_t
u_ϕ
$\mathcal{E}$
τ



monopole electric charge
$\mathcal{B}$≐0., $\mathcal{Q}$≐10., $\mathcal{P}$=0.
k=0.001, a=0.998
r_0=1.5, θ_0≐1.5
x
y
z
u_t
u_ϕ
$\mathcal{E}$
τ


monopole magnetic charge
ℬ≐0., 𝒬≐0., 𝒫=−10.
k=0.001, a=0.998
r0=1.5, θ0≐1.5
x
y
z
ut
uϕ
ℰ
τ


uniform magnetic field
$\mathcal{B} \doteq 10., \mathcal{Q} \doteq 0., \mathcal{P} = 0.$
k=0.001, a=0.998
$r_0 = 1.5$, $\theta_0 \doteq 1.5$
u_t
u_ϕ
$\mathcal{E}$
x
y
z
τ



uniform mag. field (Wald charge)
$\mathcal{B}$≐10., $\mathcal{Q}$≐39.9, $\mathcal{P}$=0.
k=0.001, a=0.998
r_0=1.5, θ_0≐1.5
x
y
z
u_t
u_ϕ
$\mathcal{E}$
τ

Radiative Penrose process

- In the rotating BH ergosphere radiated photons are attaining negative energies and negative angular momenta related to distant observer when following conditions are met by the radiating particle

$$u_t > 0, \quad u_\phi < 0$$

  $\rightarrow$ negative energy photons are emitted by the radiating charged particles, they are emitted backwards with respect to the BH rotation (radiating charged particle is counter-rotating), radiating charged particle is gaining energy.
- Photons with negative energy can never leave the ergosphere, being finally captured by the BH. These photons contribute to the spin down of the BH, which is equivalent to the extraction of the rotation energy of the BH. This is how the BH rotational energy can be extracted due to a single radiating charged particle.
- Radiative Penrose process = energy gain by a single radiating charged particle in ergosphere of rotating black hole. Energy gain effect is increased with BH rotation and EM field strength. The process of energy gain works in any EM configuration.

Astrophysical consequences & Future work

- Main problem with original Penrose process - requires interaction with other particles (collisions, decay) and the relative fragments velocity must be relativistic > 0.5 c.
- New radiative Penrose process can operate in a viable astrophysical conditions - requires existence of contra-rotating $(u_\phi < 0)$ charged particle and EM field inside ergosphere.
- Cubic dependence on the particle mass - for electrons only (when $< 10^4$ Gs)
- The energy gain by radiative Penrose process implies decrease of expected radiation in the ergosphere, but increase of the radiating energy above the ergosphere - more powerful synchrotron emission just above the ergosphere edge.

- Full GR synchrotron spectra form this new radiative Penrose prosess.
  Are there any distinguish features of this prosess (observation)?

Thank you for your attention

• M. Kološ, A. Tursunov and Z. Stuchlík: *Radiative Penrose process: Energy Gain by a Single Radiating Charged Particle in the Ergosphere...*, submitted to PRD (2020) [arXiv:2010.09481]