Electromagnetic cascades in Kerr black hole magnetospheres

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Hubble photo of the jet ejected from M87
Jets are launched very close to the event horizon!
For IC 310: horizon crossing time
\[ \Delta t = \frac{r_g}{c} = \frac{GM}{c^3} \approx 23 \text{ min} \]

Very high-energy radiation from AGN (up to TeV)

Extremely variable flares

**Gamma-ray lightcurve of the AGN IC 310 (Aleksic et al., 2014)**
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- Very high-energy radiation from AGN (up to TeV)

- Extremely variable flares

\[ \Rightarrow \text{Particles are accelerated on very small spatial scales} \]
- Correlation between radio, X-ray and gamma-ray flares
- Brightening of the radio core during flares
- Connection between particle acceleration and jet formation

(Acciari et al., 2009)
Observation of a hot spot orbiting Sgr A* by GRAVITY

Polarization measurements suggest large scale poloidal magnetic field

(GRAVITY Collaboration et al., 2018)
Context
Event Horizon Telescope

EHT image of the supermassive black hole shadow in M87

- Confirms M87* as a supermassive black hole
- Asymmetry of the ring controlled by the BH spin
- Multi-wavelength observation → black hole must be spinning
Theoretical modeling

Global picture

Ingredients:

- Spinning black hole
- Large scale magnetic field
- Hot and collisionless accretion flow
Theoretical modeling

Global picture

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- Large scale magnetic field
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Key questions:
- How is energy extracted from the black hole? (What powers the jet?)
- How is the jet loaded with mass?
- How (and where) are particles accelerated?
Theoretical modeling
Unipolar inductor

- Faraday disk rotates in a uniform magnetic fields
- Develops a potential difference between the axis and the edge
- Electric field rises from charge separation

For a spinning black hole, the electric field is **gravitationally induced**
Theoretical modeling
Blandford-Znajek mechanism

- Current carried by plasma, which extracts energy and angular momentum from the BH
- Requires a force-free magnetosphere to be activated
- Power carried by a Poynting flux
Theoretical modeling
Blandford-Znajek mechanism

- Current carried by plasma, which extracts energy and angular momentum from the BH
- Requires a force-free magnetosphere to be activated
- Power carried by a Poynting flux
- Output power prediction:

\[ L \sim 10^{46} a^2 \left( \frac{B_0}{10^4 \text{ G}} \right)^2 \left( \frac{M}{10^9 \text{ M}_\odot} \right)^2 \text{erg/s} \]

⇒ Can account for the observed power of AGN
Numerical techniques
Plasma simulations

MHD fluid simulations

1. Artificial loading of the jet (density floors)
2. No particle acceleration
3. Thermal particles only
Numerical techniques
Plasma simulations

- **MHD fluid simulations**
  1. Artificial loading of the jet (density floors)
  2. No particle acceleration
  3. Thermal particles only

- **Kinetic PIC simulations**
  - Allows us to simulate microphysics from first principles
  - Non-thermal particles
  - Unrealistic separation of scales
Numerical techniques

Description of PIC methods

Solve equation of motion \( (x^i, v^i) \)

Deposit Charge and current densities \( (\rho, J) \)

Solve Maxwell’s equations \( (E, B, D, H) \)

\[ \Delta t \]

Particle \( (e^+, e^- \text{ and photons}) \) motion and EM fields are self-consistently evolved in curved space-time

Downside: particle noise due to finite sampling of phase space
Numerical techniques
Numerical relativity

3 + 1 formulation of general relativity

- Introduces a universal coordinate time $t \rightarrow$ convenient for numerical simulations
- Allows to keep a usual PIC code architecture
- More intuition to discuss 3-dimensional quantities

(Vincent et al., 2012)
3 + 1 foliation of spacetime

\[ ds^2 = -\alpha^2 dt^2 + \gamma_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt) \]

Naturally introduces “Fiducial Observers” (FIDOs), with 4-velocity
\[ n^\mu = (1/\alpha, -\beta/\alpha) \]

- \( t \): coordinate time, reduces to proper time of an observer at infinity
- \( \alpha \): “lapse function”, so the proper time of the FIDO is \( d\tau_{\text{FIDO}} = \alpha dt \)
- \( \beta^i \): “shift vector”, 3-velocity of the FIDO with respect to the coordinate grid
- FIDOs have zero angular momentum: at rest with respect to absolute space
Numerical techniques

Field equations

- Kerr metric in spherical Kerr-Schild coordinates \((t, r, \theta, \varphi)\)

- Although in curved spacetime, we solve the usual Maxwell’s equations

\[
\begin{align*}
\partial_t B &= -\nabla \times E \\
\partial_t D &= \nabla \times H - 4\pi J,
\end{align*}
\]

where \(E\) and \(H\) are given by

\[
\begin{align*}
H &= \alpha B - \beta \times D \\
E &= \alpha D + \beta \times B.
\end{align*}
\]

- \(B\) and \(D\) are the magnetic and electric fields in the FIDO frame →
physical intuition from electrodynamics

- Spacetime acts as an active medium (constitutive relations)
Test of electromagnetic solver: check analytical solution for a magnetic monopole in Kerr spacetime

\[ A_\varphi = B_0 r_g \frac{r^2 + a^2}{r^2 + a^2 \cos^2(\theta)} \cos(\theta) \]
Equations of motion in 3 + 1 form:

\[
\frac{dx^i}{dt} = v_i = \frac{\alpha}{\Gamma} \gamma^{ij} u_j - \beta^i
\]
\[
\frac{du_i}{dt} = -\Gamma \partial_i \alpha + u_j \partial_i \beta^j - \frac{\alpha}{2\Gamma} u_j u_k \partial_i \gamma^{jk} + \epsilon \frac{\alpha}{m} F_i,
\]

where \( F \) is the Lorentz force, \( A_\mu \) is the electromagnetic 4-potential, 
\( \Gamma = \sqrt{\epsilon + \gamma^{jk} u_j u_k} \) is the FIDO-measured Lorentz factor

(\( \epsilon = +1 \) for a massive particle, \( \epsilon = 0 \) for a photon)
Particle-in-cell simulations including full GR, with vertical magnetic field

→ Reconnection and particle acceleration at the equatorial current sheet

Parfrey, Philippov & Cerutti, 2019
Numerical techniques
State of the art

Approximate injection method

Every time step, inject density
\[ \delta n \propto \frac{|D \cdot B|}{B}, \text{ provided } \frac{|D \cdot B|}{B^2} > \epsilon \]

- Development of a force-free magnetosphere
- But no chance to see a gap!

Plasma density in the current sheet
In this picture, plasma must be continuously injected in the black hole magnetosphere

- Unlikely that jet plasma originates from accretion disk

Magnetization in accreting black hole GRMHD simulations
(Porth et al., 2019)
In this picture, plasma must be continuously injected in the black hole magnetosphere

- Unlikely that jet plasma originates from accretion disk
- Magnetosphere bathed in soft background radiation field produced by the accretion flow (ADAF)
- Plausible plasma source: pair production by $\gamma\gamma$ annihilation
- If photon density low enough, formation of electrostatic gaps $\Rightarrow$ electromagnetic cascade

(Works for low-luminosity AGN, with sufficiently low accretion rates)
Radiative transfer
Pair cascade

1. Electric fields induced

Pair creation

Compton scattering
1. Electric fields induced
2. Primary particles accelerated
Radiative transfer
Pair cascade

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3. Upscattering of a soft photon to high energies ($\gamma$)

Pair creation

Compton scattering
1. Electric fields induced
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3. Upscattering of a soft photon to high energies (γ)
4. Annihilation between a γ and a soft photon

Pair creation

Compton scattering
Radiative transfer
Pair cascade

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3. Upscattering of a soft photon to high energies ($\gamma$)
4. Annihilation between a $\gamma$ and a soft photon
5. Creation of a pair that screens the electric field

Pair creation

Compton scattering
Radiative transfer
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5. Creation of a pair that screens the electric field
6. The pair flows outwards or inwards $\Rightarrow$ electric field unscreened
Radiative transfer
Pair cascade

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→ Electromagnetic cascade develops
→ Self-consistent plasma injection
Aside on the relevant surfaces:

1. **Ergosphere**: no static observer exists inside the ergoregion

(Katsoulakos & Rieger, 2020)
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2. **Null surface**: “Goldreich-Julian” plasma density of the force-free magnetosphere goes to zero

(Katsoulakos & Rieger, 2020)
Aside on the relevant surfaces:

1. **Ergosphere**: no static observer exists inside the ergoregion.

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3. **Stagnation surface**: a steady MHD flow has zero velocity.

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Aside on the relevant surfaces:

1. **Ergosphere**: no static observer exists inside the ergoregion

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3. **Stagnation surface**: a steady MHD flow has zero velocity

4. **Outer light surface**: similar to the pulsar light cylinder, a point orbiting at angular velocity $\Omega$ goes superluminal

5. **Inner light surface**: specific to Kerr black holes, an orbiting point goes superluminal because of spacetime dragging
Radiative transfer
Principle

▶ Particles bathed in a soft radiation field (uniform, isotropic, *monoenergetic*)

▶ High-energy \( \gamma \) photons added as a 3\(^{rd} \) species

▶ \( \gamma \) photons can **pair produce** against soft field, \( e^\pm \) can produce \( \gamma \) photons by **scattering** off soft field

▶ Semi-analytical to save computation time

▶ **Monte-Carlo** algorithm: an interaction occurs if

\[
p < 1 - e^{-\delta \tau}
\]

where \( p \in [0, 1] \) is a random number and \( \delta \tau \) is the optical depth traversed by a particle between two time steps
Test: isotropic initial distribution of monoenergetic particles with Lorentz factor $\gamma_e$ in a monoenergetic radiation field with energy $\varepsilon_0$

$\varepsilon_0/mc^2 = 0.01, \gamma_e = 100.0$

$\varepsilon_0/mc^2 = 0.1, \gamma_e = 200.0$

$\Rightarrow$ Fits well the analytic prediction in the Thomson ($\varepsilon'_0 \ll m_e c^2$) and Klein-Nishina ($\varepsilon'_0 \gg m_e c^2$) regimes
- $e^\pm$ pairs can only be created if the photons have sufficient energy: 
  \[ \varepsilon_1 \varepsilon_0 \gtrsim (m_e c^2)^2 \]

- Pair production cross section peaks at the threshold 
  \[ \varepsilon_1 \varepsilon_0 \simeq (m_e c^2)^2 \]

⇒ Fits well the analytic prediction close to, and far from the pair creation threshold
Numerical methods
Simulation setup

- 2D axisymmetric simulation
- Initial magnetic monopole configuration
- Maximally spinning black hole: $a = 0.99$
- Start with a monoenergetic, isotropic, uniform distribution of photons
Key parameters

- **Opacity** \( \tau_0 = n_s \sigma_T r_g \), where \( n_s \) is the background radiation field density
- **Magnitude of the magnetic field** \( \tilde{B}_0 = r_g e B_0 / m_e c^2 \)
- **\( \tilde{\varepsilon}_0 = \varepsilon_0 / m_e c^2 \)** energy of the background radiation field
Numerical methods
Parameter scalings

Key parameters

- Opacity $\tau_0 = n_s \sigma_T r_g$, where $n_s$ is the background radiation field density
- Magnitude of the magnetic field $\tilde{B}_0 = r_g e B_0 / m_e c^2$
- $\tilde{\varepsilon}_0 = \varepsilon_0 / m_e c^2$ energy of the background radiation field

In M87*, $\tilde{B}_0 \sim 10^{14}$ and $\tilde{\varepsilon}_0 \sim 10^{-9}$; in practice we have a smaller separation of scales, which must satisfy

$$1 \ll \gamma_s \ll a \tilde{B}_0,$$

where $\gamma_s = 1 / \tilde{\varepsilon}_0$ is the Lorentz factor of the bulk of the particles

We kept $\tilde{\varepsilon}_0 = 0.005$, $\tilde{B}_0 = 5 \times 10^5$ fixed
Results
Magnetospheric structure
Phase space plot of the freshly created pairs
Results
Bursts and gap location

Time averaged parallel electric field

- Gap opens at the **light surface**, then moves inwards or outwards
- Conclusion holds for lower spin $a$
- Gap size: larger than plasma skin depth, smaller than horizon radius $r_g$
Results
Bursts and gap location

- Bursts of pair creation at short time scales (a fraction of $r_g/c$)
- Dissipated power around 3% of the total Poynting flux
- Pair creation occurs in these “flying gaps”

Crinquand et al., 2020
Results
Transition between two regimes

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Pair cascade in Kerr magnetospheres
Results
Transition between two regimes

- Low opacity: large gap, pair creation occurs at larger distances, more dissipation ⇒ higher density achieved outside the gap
- High opacity: gap screened completely, self-regulation gives rise to pair creation bursts
- Almost force-free behaviour
Results
Transition between two regimes

- Output power matches BZ prediction
  \[ L_{\text{BZ}} = \frac{B_0^2 \omega_{\text{BH}}^2}{6} \]
- Dissipation goes down as opacity increases
- Most energy transferred to low-energy photons (beyond pair creation threshold)

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Pair cascade in Kerr magnetospheres
Conclusion

Results: (see Crinquand et al. for details)

1. Blandford-Znajek process can be activated
2. Plasma supply of the jet explained
3. Time dependent gap at the inner light surface

Now we have to link with observations!
Disk simulations
Context

- Need of a more realistic magnetic configuration
- Interaction with an accretion disk?
- How does magnetic reconnection at the current sheet impact pair creation at the poles?

(Komissarov & McKinney, 2007)
Start with paraboloidal magnetic field \( A_\varphi = \left( \frac{r + r_0}{r_h + r_0} \right)^\nu (1 - |\cos \theta|) \)

→ Presence of an equatorial current sheet

→ Enables us to have an outflow, as both light surfaces are crossed by field lines

Problem: All magnetic flux gets dissipated
We implemented a perfectly conducting disk as boundary conditions for the fields, simulating an accretion disk, that anchors the fields lines.

→ Allows the simulation to reach a stationary state
Initially, magnetic flux dissipated by reconnection at the current sheet

Accretion of giant plasmoids provides the BH with magnetic flux

Polar cap discharge ignited by accretion of plasmoids?

Time-dependent behaviour
So far, only high-energy photons above the pair creation threshold were simulated.

- Background field with uniform opacity → These photons are quickly absorbed.

Goal: reproduce variability and explain high-energy emission from AGN → Need to simulate photons below the pair creation threshold and reconstruct a lightcurve.
Disk simulations

Lightcurves

- Photons below the PP threshold no longer interact with the rest of the simulation
- Far enough from the BH, they propagate in straight lines
- Collect all photons with a fixed outgoing viewing angle
- Accounts for the propagation time delay to the observer:

\[ \Delta t_d = \frac{PS \cdot e_{\text{obs}}}{c} \]

(Cerutti et al., 2016)
Lightcurve for different viewing angles

- Enhanced variability when looking at higher latitudes (polar emission), but lower intensity
- Sub-horizon scale variability is hard to resolve
- Periodicity of a few $r_g/c$, visible in the movies → flares?
Use of the geokerr code, by J. Dexter and E. Agol

- Computes photon geodesics in Kerr spacetime using semi-analytical formulation
- Allows to compute efficiently the outgoing directions and time delays of photons as soon as they are emitted

We are working on coupling it to Zeltron, to produce time and angle-resolved lightcurves

*(Dexter & Agol, 2009)*