Models for Sgr A* flares:
from a general analytical to magnetic reconnection model

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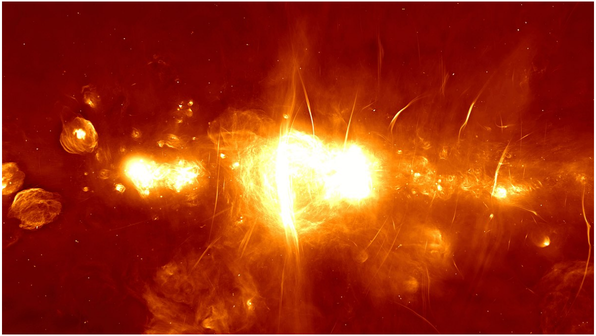

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l'Observatoire de Paris

Outline

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Sgr A*: SMBH at the center of the Milky Way

- $d \approx 8$ kpc
- $M_{\text{SMBH}} \approx 4 \times 10^6\, M_\odot$
- Radiatively-inefficient accretion flow (high temperature, low density)

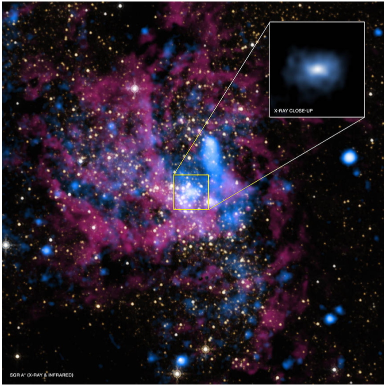
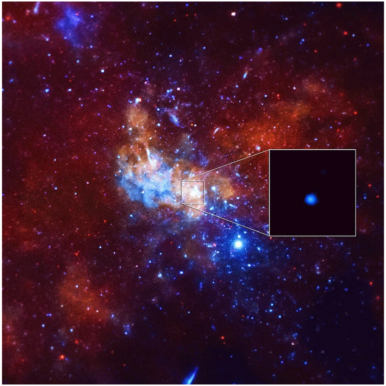


Figure: IR view of Sgr A* and zoom in X-rays into the core region. Source: NASA

Sgr A*: flaring activity at the heart of the Milky Way

– Flaring activity in *sub-millimeter*, *infrared*, and *X-ray* bands



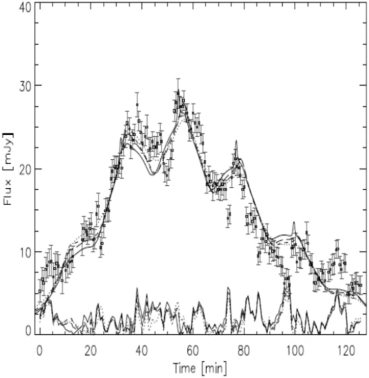
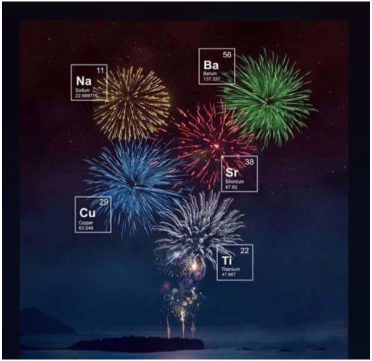


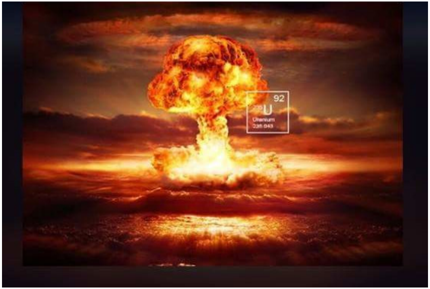
Figure:
(*left*) Chandra detection of a bright X-ray flare from Sgr A* (2013) (source: NASA).
(*right*) Example of a Sgr A* flare light curve (L-band) (Hamaus et al. 2009)

Questions to be addressed

? What is the origin of Sgr A* flaring behavior ?

? Which physical processes launch the "fireworks" ?





?? What is going on in the vicinity of supermassive black holes ??

GRAVITY instrument

- Operates in K band (near-infrared): **2 - 2.4 μm**
- Performs precision *narrow-angle astrometry* and *interferometric imaging* by phase referencing
- Combines near-infrared light from four VLTI telescopes
- Astrometry precision of $\sim 10\,\mu$as
- Imaging resolution of $\sim$ 4 mas

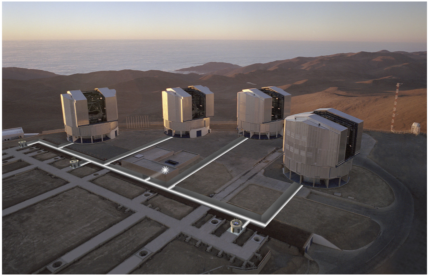


Figure: (*left*) The Very Large Telescope Interferometer (VLTI) in Chile (credit: ESO). (*right*) GRAVITY instrument at VLTI (credit: MPE/GRAVITY team)

Sgr A* flares observed with GRAVITY

GRAVITY resolved locations of three bright flares in 2018:

- A bright spot moving around the SMBH very close to it with *elliptical* trajectory, however having an *offset* relative to the location of the SMBH
- $t_{\rm flare} \sim 40$ min corresponds to orbit at 3.5 R_s, while the observed ellipse axis is $\sim$ 100 μas $\rightarrow$ 10 R_s $\Rightarrow$ **SUPER-KEPLERIAN MOTION**
- Flare light curves have very different shapes (single- and double-peaked).

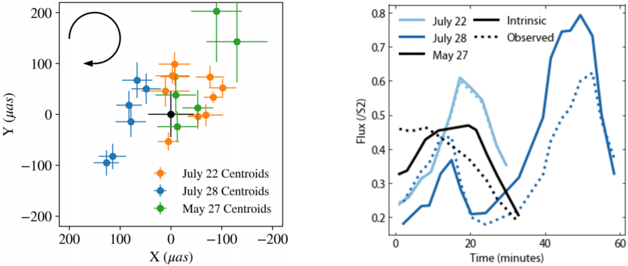


Figure: (*left*) Apparent motions of flaring region during three Sgr A* 2018 flares seen by GRAVITY (Ball et al. 2020). (*right*) Light curves of the three flares (Gravity Coll. et al. 2020)

Outline

Example of the simplest model: "hot-spot"

The model was considered by various authors.
A generic "hot-spot" model includes:

LOW STATE: (Vincent et al. 2019)

- Magnetized compact **torus**
  - Thermal *synchrotron* emission
- Extended **jet**
  - κ *synchrotron* emission

FLARING STATE:

- A **blob** rotating around the central SMBH in equatorial plane
  - κ *synchrotron* emission

Not very physically motivated scenario

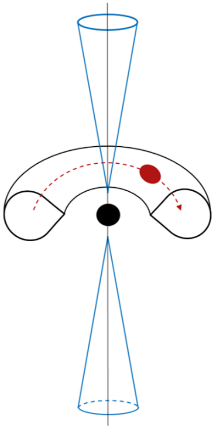


Figure: Hot-spot model for Sgr A* flaring activity (credit: N. Aimar)

Magnetic reconnection and **plasmoid formation** are assumed to be the key processes launching the flare in this model

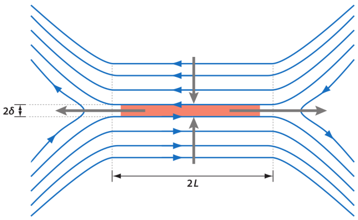


Figure: A scheme of magnetic reconnection process (source: Zweibel & Yamada 2009)

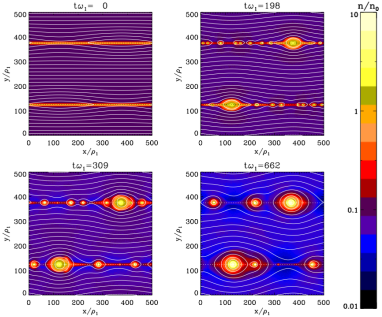


Figure: Plasmoid formation during magnetic reconnection (source: Cerutti et al. 2013)

The plasmoid model by Ball et al. 2020

Heating phase:

- **Magnetic reconnection**:
  - Plasmoid formed close to the SMBH and ejected into coronal region
  - Relativistic *thermal* e^- distribution with linearly $\nearrow$ n_e, $\theta_e = \text{const}$

Cooling phase:

- $n_e = \text{const}$, temperature is $\searrow$

  $\gamma(t) = \gamma_0(1 + A\gamma_0 t)^{-1}$, $\theta_e = \gamma/3$

  Valid only for an individual e^- and not for a distribution !

Explains well the observed offset in astrometry and shape of light curves

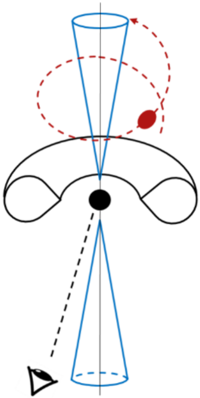


Figure: Plasmoid model for Sgr A* flaring activity (credit: N. Aimar)

Outline

Our flare model: assumptions and approach

>> We extend the Sgr A* flare model by Ball et al. 2020

- Emitting region: **plasmoid** filled with *electron-proton* plasma
- Synchrotron radiation produced by HE particles
- **Heating phase**: **Magnetic reconnection**
  - Many small plasmoids are ejected into coronal region and merge together:

    R ↗ linearly with time from $R_{\rm min} = 0.2 GM_{\rm BH}/c^2$ to $R_{\rm max} = GM_{\rm BH}/c^2$

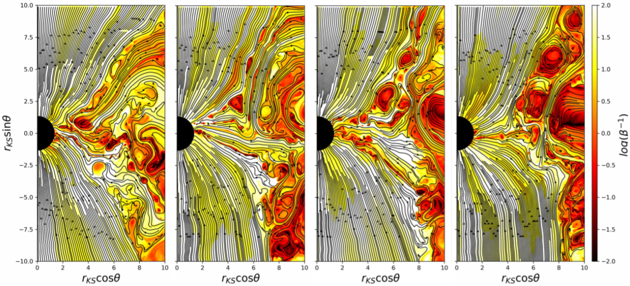


Figure: GRMHD simulations of a growing plasmoid (Ripperda et al. 2020)

- **Plasmoid orbits:** *equatorial* and *helical* motion
- **Injection** of κ distribution at a *constant* rate ($\Rightarrow n_{\rm e} \nearrow$ linearly) during $t_{\rm inj} \sim L/v_{\rm rec} \sim L/(0.1 v_{\rm A})$ (Ball et al. 2018), $t_{\rm inj} \sim 15$ min

$$\kappa(\gamma, \theta, k) = \frac{N}{4\pi}\gamma(\gamma^2 - 1)^{1/2}\left(1 + \frac{\gamma - 1}{k\theta}\right)^{-(k+1)}$$

- **Cooling phase**:
  - $t_{\rm cool}(\gamma) \simeq (b_{\rm cool}\gamma)^{-1}$, $t_{\rm cool} \sim 30$ min (at $\gamma \sim 10^3$)

$\rightarrow$ **We treat the evolution of e^- spectrum with kinetic approach**

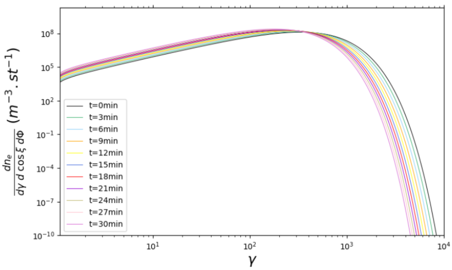
$$\boxed{\frac{\partial N_{\rm e}(\gamma, t)}{\partial t} = \frac{\partial}{\partial \gamma}\left[b_{\rm cool}\gamma^2 N_{\rm e}(\gamma, t)\right] + Q_{\rm inj}(\gamma, t)}$$

We compute **electron spectrum** and associated **synchrotron SED** numerically using `EMBLEM` time-dependent radiative code (Dmytriiev et al. 2021)

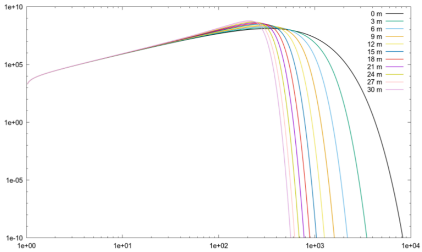
Cooling phase: approximation vs full calculation

We compare the e^- spectrum evolution computed using simplified cooling description (Ball et al. 2020), and using the EMBLEM code.

Ball et al. 2020



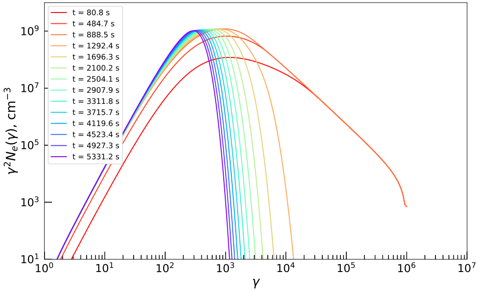
Full simulation of e^- spectrum evolution



VERY PRELIMINARY

⇒ **Approximation by Ball et al. 2020 is too simplistic. A full simulation is required for adequate flare description**

$N_e(\gamma, t)$



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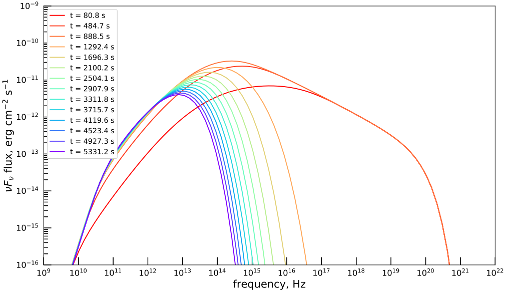
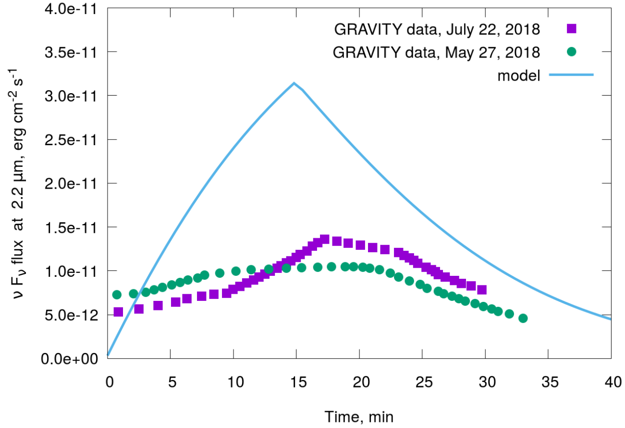
SED



We compare the *model light curve* at 2.2 μm to unfolded *GRAVITY data* of two Sgr A* 2018 flares (Gravity Collaboration et al. 2020)

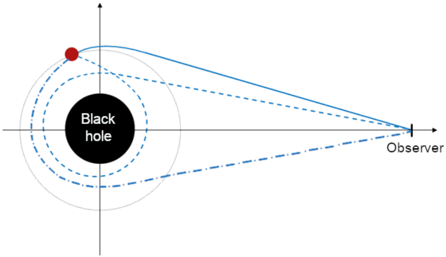
VERY PRELIMINARY



– Need to adjust the physical parameters of the source !

We take into account the effects of *general relativity* (GR):

- Take α_ν and j_ν computed with the radiative EMBLEM code
- Give as an input to the ray-tracing GYOTO code (Vincent et al. 2011)
  - Performs backward ray tracing along null geodesics (from the observer towards the BH)
  - Integrates the radiative transfer equation



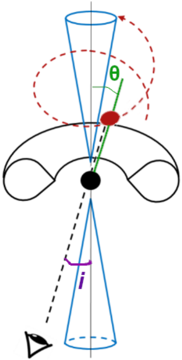
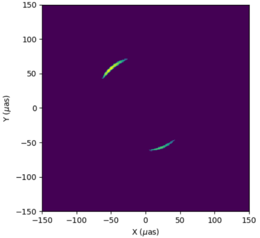


Figure: Light propagation near a BH: formation of multiple images from a distant source in a curved space-time (credit: N. Aimar, modified: A. Dmytriiev)

- *Helical motion* of the plasmoid near the SMBH
- *Strong lensing*: inclination $\approx \theta_0$ (plasmoid behind the SMBH)
- *Multiple peaks* in the LC: primary and secondary images, and strong lensing

FoV $= 300\ \mu$as



PLAY: external link

VERY PRELIMINARY

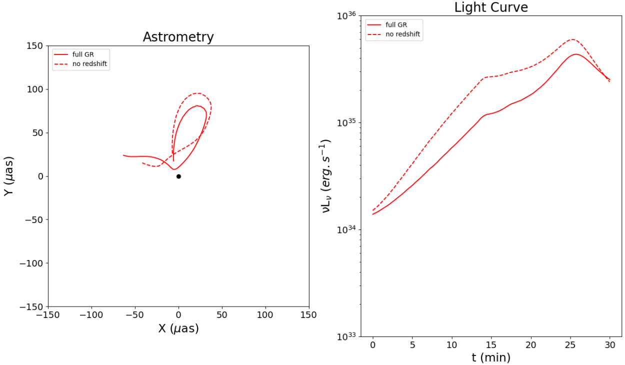


Figure: Observed centroid position of the plasmoid (left) and light curve (right) during the flare taking into account GR effects (*for a very specific set of orbital parameters*!) (credit: N. Aimar)

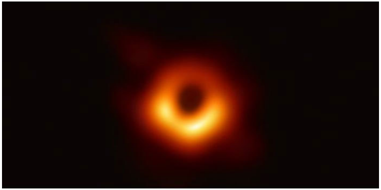
Outline

Summary

- We have developed a physical model for Sgr A* flares by extending the existing models in the literature
- The flares are triggered by **magnetic reconnection**
- We calculate the evolution of *electron spectrum* in the plasmoid and the associated broad-band *synchrotron emission* (source frame)
- We include the **effects of GR** on the light propagation near the SMBH and hence compute the *IR light curve* and *astrometry* of the flare as seen by a distant observer
- A large variety of light curves and astrometry can be produced by the model by considering different sets of parameters
- The model is able to provide a qualitative representation of the Sgr A* flare light curves measured by GRAVITY in 2018, as well as naturally explains the observed offset of the orbit

This is work in progress, but current results look promising!

- Include SSC emission in the model (already handled by `EMBLEM` code) for a better treatment of X-rays
- Fit the physical parameters of the source: B, θ, k, $n_{\mathrm{e,max}}$, etc
- Adjust the parameters of the plasmoid orbit



enhances further