Synthetic Images of Plasma at the Black Hole Event Horizon

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BLACK HOLE CAM

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Plasma dynamics close to the BH

- A goal: comparison of realistic models of accretion flows and jets to EHT observations to find out what Sgr A* radio source is

- solve ideal–MHD equations on the standard Kerr metric background or other metric (MHD models in alternative gravity theories developed by BHCAM–Frankfurt)

- set initial conditions until quasi-stationary solution is obtained

- feed the simulation into the radiative transfer code to calculate the apperance which depends on
  - MHD simulation parameters (≥ 5)
  - radiative transfer parameters (≥ 6)

Simulations initial conditions for fluid and the ”expensive” parameters

- rotating torus (donut) in hydrostatic equilibrium - analytical solution found in 70ties

- size of the torus
  - $R_{in} = 6\,GM_{\mathrm{BH}}/c^2$
  - $R_{max} = 12\,GM_{\mathrm{BH}}/c^2$
  - reliable disk solution within $\sim R_{max}$

- spin of the BH: $a \in (0, 0.98)$

- size of the computational domain: $R_{out} = 40, 240\,GM_{\mathrm{BH}}/c^2$ or larger if we want to model multiwavelength emission from jets

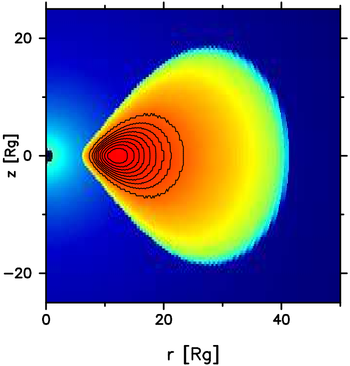

Fig: 2-D slice at initial time: density (color) and magnetic field geometry (lines)

Simulations initial conditions for B-fields and the ”expensive” parameters

- B-field topology: dipole loop
- B-field strength (parameterized by $\beta_{init,max} = P_{\rm gas}/P_{\rm mag}$)
- weak B-fields: $\beta_{max,init} = 200$; disk known to be unstable (magnetorotational instability)
- for dipole formation of a jet is guaranteed and no large scale field cancellations (reconnections in the ideal-MHD simulations produce an artificial variability)

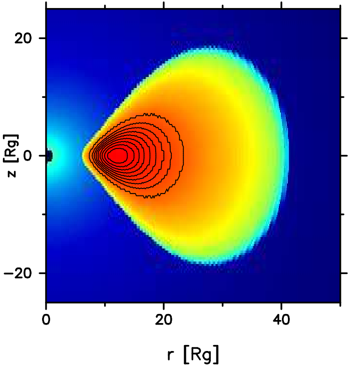

Fig: 2-D slice at initial time: density (color) and magnetic field geometry (lines)

Simulations tools

- models extensively studied in last decade; other flavors: magnetically arrested disks (big torus with weak B-fields = eventually more magnetic flux accumulates near the BH and magnetic barrier forms), thin disks, tilted disk (BH and disk angular momentum vector misaligned) . . .

- HARM-3D (Scott Noble version)

- BHAC (new code developed by BHCAM–Frankfurt)
  - has AMR to better resolve areas of interests e.g., the jet-disk boundary
  - will have resistivity for physical reconnections (other B field topologies will be possible soon)
  - we hope to capture more physics with the new simulations

Plasma dynamics close to the BH - spin dependence

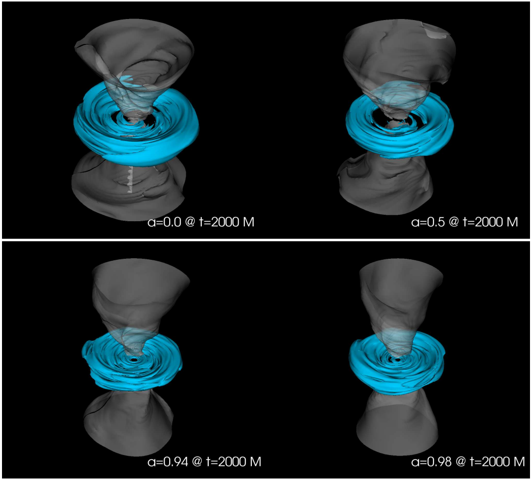

Fig: Constant density contours of a 3-D GRMHD model, HARM3D, 25 light crossing times ($R_{out} = 40GM_{\rm BH}/c^2$), res: $192 \times 128 \times 64$ in log spherical-polar coordinates ($N_{\log r} \times N_\theta \times N_\phi$), computation of 1 model = 24-40h on 192 CPU cores on Radboud University computer cluster

MOVIE

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Known parameters for the radiative transfer code

$\mathbf{M_{BH}}$ - mass of the black hole

- to convert geometrized unit system (G=c=1) to something useful:
  - size conversion: $[R_g] \rightarrow$ [cm]
  - time conversion: $[R_g] \rightarrow$ [seconds].
- $M_{Sgr\ A*} = 3.86 \pm 0.14 \times 10^6 M_\odot$ (Chatzopoulos et al. 2015)
- $M_{M87} = 3.2, 3.5$, and $6.2^{+0.9}_{-0.7} \times 10^9 M_\odot$ (Macchetto et al. 1997, Walsh et al. 2013, Gebhardt et al. 2011)

D - distance to the radio source

- to convert Intensity of radiation into flux
- to scale the size of the model on the sky
- $D_{Sgr\ A*} = 8.27 \pm 0.1 kpc$ (Chatzopoulos et al. 2015)
- $D_{M87} = 16.7 \pm 1.1 kpc$ (Mei et al. 2007)

Unknown parameters for the radiative transfer code

Geometry parameter

i - our viewing angle

Geometry parameter

PA - position angle of BH spin on the sky

Plasma physics

T_p/T_e - describes coupling of electrons and protons in collisionless plasma

$$\frac{T_p}{T_e} = R_{high}\frac{b^2}{1+b^2} + R_{low}\frac{1}{1+b^2} \tag{1}$$

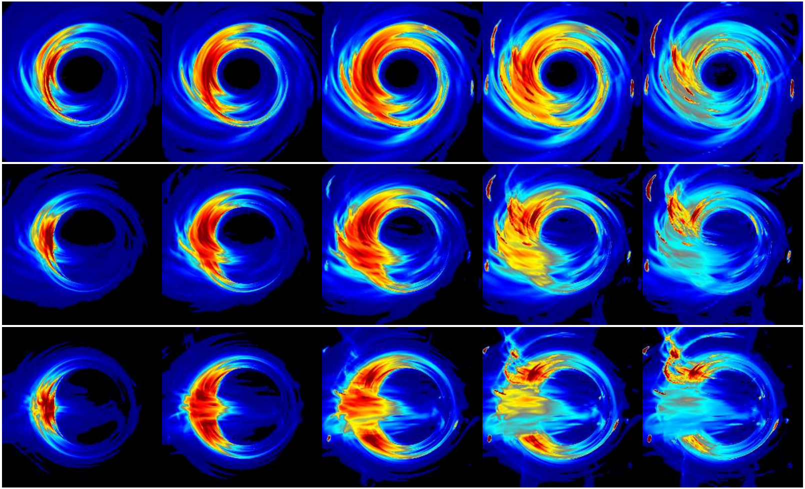
where $b = \beta/\beta_{crit}$ and $\beta = P_{gas}/P_{mag}$. $\beta_{crit} = 1$ (also a parameter), R_{high} and R_{low} are free parameters $\in (1, 100)$

Radiation flux normalization

- mass of the accretion disk or $\dot{\mathbf{M}}$ ($\sim 10^{-9} - 10^{-7} M_\odot yr^{-1}$)
- normalize the model to 2.4 Jansky (normalzation depends on i, T_p/T_e, and GRMHD parameters e.g., a)

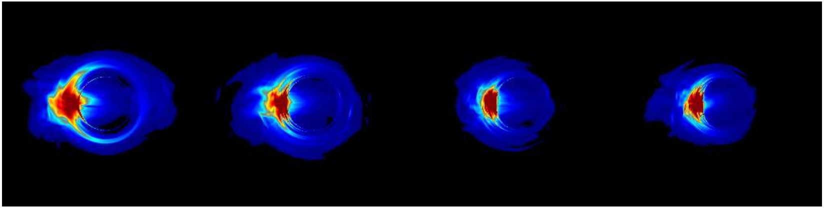
Examples of GRMHD models scaled to Sgr A*
Synchrotron intensity maps at λ =1.3mm

ep coupling effect (disk to jet dominated - left to right) and viewing angle (30-90, top to bottom

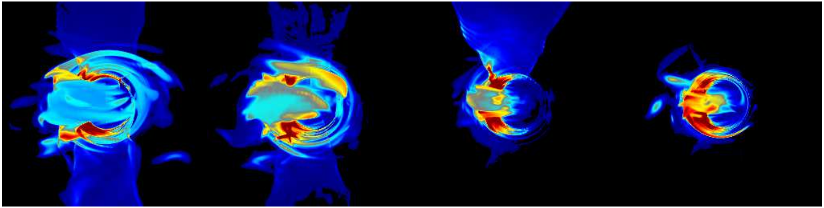


Spin, $i = 90$

Disk emission dominated a=(0,0.5,0.94,0.98):



Jet emission dominated a=(0,0.5,0.94,0.98):



Time, $a = 0.94$

Disk emission dominated i=(30,60,90,120,150):

MOVIE 1

Jet emission dominated i=(30,60,90,120,150):

MOVIE 2

Other options in our imaging code

DONE

- non-MHD models: analytical hot spots, analytical models of advection dominated accretion flows
- electron distribution functions: thermal (T_e) + power-law (η, p, $\gamma_{min}, \gamma_{max}$)
- convolution with arbitrary scattering, visibility, closure stuff calculator (we can make a robust comparison, but no fitting the model to the data)
- synthetic images can be used to test e.g. various image reconstruction methods

UNDER DEVELOPMENT AT RADBOUD UNIVERSITY

- evolution of the polarization tensor in the plasma frame

FUTURE

- interface with MeqTrees package to perform the Bayesian analysis for parameters chosen in a Monte Carlo fashion

END