Black holes in computers

Relativistic jets in progenitors of gamma-ray-bursts

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Force-free magnetospheres in computers

Focusing on electrodynamics around compact objects

Goal: Scalable code for the simulation of *force-free* magnetospheres on the dynamical metric of *compact objects* (e.g., neutron stars or black holes).

Physics: In the limit of high field energy (low particle inertia), General Relativistic magnetohydrocynamics (GRMHD) reduces to *General Relativistic force-free electrodynamics (GRFFE)*.

[1] Full Maxwell's equations evolution

(Komissarov, 2002, 2004, 2007; Paschalidis and Shapiro, 2013)

$$\nabla_\nu F^{\mu\nu} = J^\mu \qquad \nabla_\nu {}^*F^{\mu\nu} = 0$$

[2] Energy flow evolution

(McKinney, 2006; Paschalidis and Shapiro, 2013; Etienne et al., 2017)

$$\nabla_\mu T^\mu_{\ \nu} = 0 \qquad \nabla_\nu {}^*F^{\mu\nu} = 0$$

- *Explicit* methods on *structured* grids (well suited for hyperbolic, non-stiff equations)
- *Conservative* schemes require computing a unique *flux* per numerical zone (exact and HLL *Riemann solvers*)
- Cover a variety of time and length scales (e.g., at *current sheets*). This requires adaptivity of the *mesh*, highly accurate regions, and parallel scalability.

Simulations of Blandford/Znajek process

Setting up a generic GRFFE problem

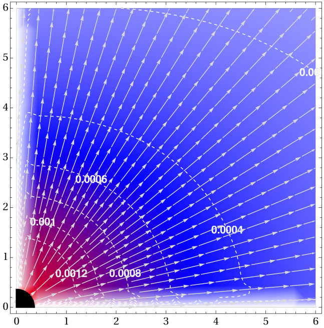


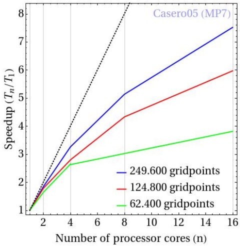
Figure: Visualization of the mag. field (**B**) initial data around the BH (mass $m = 1$, spin $a = 0.9$). A numerical solution to the Grad-Shafranov equation is obtained via the solver architecture in the *CoCoNut* code (cf. Adsuara et al., 2016) and as initial data for simulations employing the *Einstein Toolkit*.

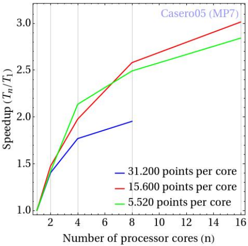
- The numerical techniques solving the Grad-Shafranov equation around spinning Kerr BHs may be used with existing infrastructure of numerical PDE solvers, e.g., the *CoCoNut* code. (Cerdá-Durán et al., 2009; Adsuara et al., 2016)
- Spacetime initial data for rapidly spinning BHs (high Blandford/Znajek luminosities expected) is tested on the *Carpet* grid of the *Einstein Toolkit*. (Liu et al., 2009)
- We have adapted the evolution routines available for the ET to account for a FF magnetized plasma around spinning BHs implemented as *punctures*. Our implementation is inspired by previous work on GRMHD using the ET and GRFFE. (Faber et al., 2007; Mösta et al., 2014; Etienne et al., 2017)

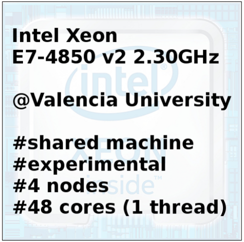
Scaling tests need scalable architectures

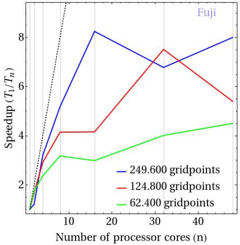
Parallel tests of `GRiFFiN` code - way to go!

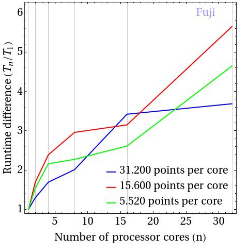
Tearing mode scaling tests on static (flat) background. *Einstein Toolkit* shows weak scalability (Löffler et al., 2012) on selected large machines.











Open forum: Let's discuss

Questions. Answers. Remarks. Discussion.

Thank you.

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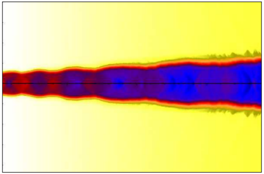
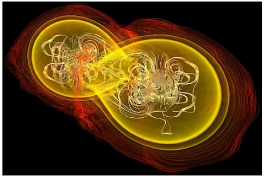
How numerical simulations (may) help us

Examples from CAMAP/Valencia

Neutron star mergers forming a rotating *black hole* with magnetized environment. (Rezzolla et al., 2011; Kiuchi et al., 2014; Ruiz et al., 2016)



Goal: Application of established numerical techniques within other disciplines (e.g., astroeye).

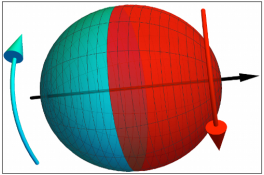


Goal: Probing of specific mechanisms (e.g., *dissipation*, *radiation*) and development of numerical codes/strategies.

Interdisciplinary work, e.g., a joined project of mathematicians, theoretical physicists and optometrists at the *University of Valencia*.

Goal: Access to astrophysical scenarios (e.g., *binary mergers*, gravitational waves, *jets*).

Numerical simulation of *jet* propagation (Mimica et al., 2013).



Relativitic jets are very strong accelerators
Observation of cosmic high energy phenomena

- *Jets* are highly *collimated* outflows from compact objects.
- Very high *Lorentz factors* are possible.
- Both internal and external *shocks* are subject of current studies and simulations.
- *Dissipative* mechanisms occur in interaction with the *interstellar medium*.

Open questions remain mainly in jet launching and collimation.

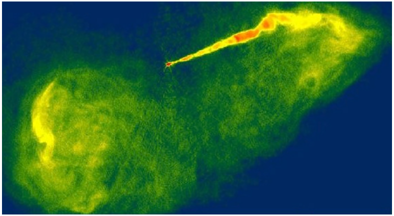


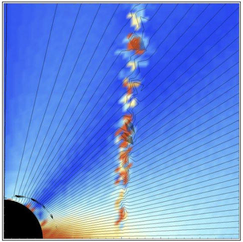
Figure: *Top:* Pulsar IGR J11014-6103 (Chandra X-ray observatory). *Bottom:* M87 radio galaxy (National Radio Astranomy Observatory).

Research stages and methods

Numerical simulations as astrophysical experiments

Stage I: **Theory/Numerics**

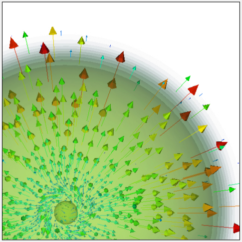
Grad-Shafranov initial data



- Implementation and testing of a numerical procedure for *magnetosphere* data.
- Expand solving schemes towards more *complicated field topologies*.

Stage II: **Simulations**

Einstein Toolkit setup



- Preparation of initial data for time evolution setups.
- Adaptation of suitable evolution schemes (employing the *Einstein Toolkit*).

Stage III: **Evaluation/Feedback**

Fortran code segment

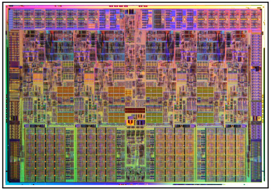
```
call Compute_Function_Value(PsiGrid(i,j,k), ITmp
! Linear operator coefficients >>>>>>>>>>>>>>>>>
! Linear terms from BZ77 - Simplified in Mathemat
c1(1,1,i,j,k) = (1.0d0/SigmaBL**2.0d0)* &
     (2.0d0*bhspin_sq*cBL_sq*(bhmass+OmegaTmp*sBL
     bhspin_sq*(bhmass-rBL)*OmegaTmp*sBL_sq))+ &
     2.0d0*rBL*((-bhmass)*rBL+OmegaTmp*sBL_sq*(2
c11(1,1,i,j,k) = ((2.0d0*bhmass-rBL)*rBL-bhspin_
     bhspin_sq*(bhspin_sq-2.0d0*bhmass*rBL+rBL_s
c2(1,1,i,j,k) = (32.0d0*(bhspin_sq+rBL_sq)*Delta
     (-8.0d0*bhspin_sq*(3.0d0*bhspin_sq+4.0d0*rBL
     (5.0d0*bhspin**6.0d0+16.0d0*rBL**6.0d0+16.0
     4.0d0*bhspin_sq*(-bhspin_sq+4.0d0*bhspin*bh
     sin(4.0d0*theta(j))+bhspin**4.0d0*DeltaBL*O
     (32.0d0*DeltaBL*SigmaBL**2.0d0)
c22(1,1,i,j,k) = ((2.0d0*bhmass-rBL)*rBL-bhspin_
     bhspin_sq*(bhspin_sq-2.0d0*bhmass*rBL+rBL_s

! Non-linear operator coefficients >>>>>>>>>>>>>
! Non-linear terms from BZ77 - Simplified in Math
if ((i.lt.1).or.(i.gt.m).or.(j.lt.1).or.(j.gt.n)
   Source(i,j,k)=0.0d0
else
   Source(i,j,k)= (-((sBL_sq)*(-2.0d0*bhspin*bhma
```

- Classify initial data in terms of *stability* and the observation of *jet launching*.
- Understand the role of force-free evolution vs. ideal MHD implementations.

How to contribute to the community?

Key drivers: Complexity and cost reduction

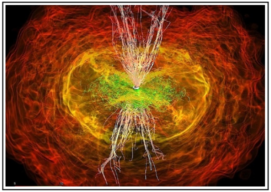
Intel i7 processor



Despite *parallelized codes*, large computational power is required for simulation projects and everyday work:

- Rezzolla et al. (2011) project required $\sim$ 200.000 *core hours*.
- CAMAP used $\sim$ 250.000 core hours in wide-area computer centers the last 4 month (more that 5 million the last 5 years).

Post-merger data



Relativistic jets are a post-merger phenomenon, hence, the (violent) merger simulation is not required **if** physical initial data could be used instead:

- Reduction of numerical complexity of the employed code.
- Faster access to relevant simulation episodes (in order to do theoretical astrophysics).

Time evolution of FF electrodynamics I

Comparison of evolution schemes

[1] Full Maxwell's equations evolution

(Komissarov, 2002, 2004, 2007; Paschalidis and Shapiro, 2013)

$$\nabla_\nu F^{\mu\nu} = J^\mu \qquad \nabla_\nu {}^*F^{\mu\nu} = 0$$

Augmented system

(Dedner et al., 2002; Palenzuela et al., 2009; Mignone and Tzeferacos, 2010)

$$\nabla_\nu \left({}^*F^{\mu\nu} + \left({c_h}^2 \gamma^{\mu\nu} - n^\mu n^\nu \right) \psi \right) = -\kappa_\psi k^\mu \psi$$

$$\nabla_\nu \left(F^{\mu\nu} + g^{\mu\nu} \phi \right) = J^\mu - \kappa_\phi k^\mu \phi$$

[2] Energy flow evolution

(McKinney, 2006; Paschalidis and Shapiro, 2013; Etienne et al., 2017)

$$\nabla_\mu T^\mu{}_\nu = 0 \qquad \nabla_\nu {}^*F^{\mu\nu} = 0$$

Augmented system

(Dedner et al., 2002; Palenzuela et al., 2009; Mignone and Tzeferacos, 2010)

$$\nabla_\nu \left({}^*F^{\mu\nu} + \left({c_h}^2 \gamma^{\mu\nu} - n^\mu n^\nu \right) \psi \right) = -\kappa_\psi k^\mu \psi$$

The div$\mathbf{B} = 0$ and div$\mathbf{D} = \rho$ constraints are ensured by a mixed *hyperbolic/parabolic* correction with the additional scalar potentials ψ and ϕ. In its analogy to the *telegraph equation*, the factor c_h is the finite propagation speed of divergence errors, the constants κ_ψ and κ_ϕ are their damping rate. The above equations are formulated in a *conserved flux formulation*:

$$\partial_t \mathcal{C} + \partial_j \mathcal{F}^j = \mathcal{S}_n + \mathcal{S}_s$$

Time evolution of FF electrodynamics II

Conserved flux formulation (dynamic spacetimes)

[1] Full Maxwell's equations evolution

- Requires *(force-free) currents* (cf. Komissarov, 2011)
- Fluxes derived from *conserved* quantities

$$\mathcal{C} \equiv \gamma \begin{pmatrix} \frac{\psi}{\alpha} \\ \frac{\phi}{\alpha} \\ B^i + \frac{\psi}{\alpha}\beta^i \\ D^i - \frac{\phi}{\alpha}\beta^i \end{pmatrix} \qquad \mathcal{F}^j \equiv \gamma \begin{pmatrix} B^j - \frac{\psi}{\alpha}\beta^i \\ -\left(D^j + \frac{\phi}{\alpha}\beta^i\right) \\ e^{ijk}E_k + \alpha\left({c_h}^2\gamma^{ij} - n^i n^j\right)\psi \\ -\left(e^{ijk}H_k + \alpha g^{ij}\phi\right) \end{pmatrix}$$

$$\mathcal{S}_n \equiv \begin{pmatrix} -\gamma\alpha\psi\,\Gamma^t_{\alpha\beta}\left({c_h}^2\gamma^{\alpha\beta} - n^\alpha n^\beta\right) \\ -\gamma\alpha\phi\Gamma^t_{\alpha\beta}g^{\alpha\beta} - \gamma\rho \\ -\psi\left[\alpha\gamma\Gamma^i_{\alpha\beta}\left({c_h}^2\gamma^{\alpha\beta} - n^\alpha n^\beta\right)\right] \\ -\gamma\alpha\phi\Gamma^i_{\alpha\beta}g^{\alpha\beta} - \gamma J^i \end{pmatrix} \qquad \mathcal{S}_s \equiv \begin{pmatrix} -\alpha\gamma\kappa_\psi\psi \\ -\alpha\gamma\kappa_\phi\phi \\ 0 \\ 0 \end{pmatrix}$$

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[2] Energy flow evolution

- **D** is reconstructed ($\mathbf{D}\cdot\mathbf{B} = 0$)
- Fluxes derived from *primitive* quantities

$$\mathcal{C} \equiv= \gamma \begin{pmatrix} \frac{\psi}{\alpha} \\ B^i + \frac{\psi}{\alpha}\beta^i \\ \alpha T^t{}_i \end{pmatrix} \qquad \mathcal{F}^j \equiv \gamma \begin{pmatrix} B^j - \frac{\psi}{\alpha}\beta^i \\ e^{ijk}E_k + \alpha\left({c_h}^2\gamma^{ij} - n^i n^j\right)\psi \\ \alpha T^i{}_j \end{pmatrix}$$

$$\mathcal{S}_n \equiv \begin{pmatrix} --\gamma\alpha\psi\,\Gamma^t_{\alpha\beta}\left({c_h}^2\gamma^{\alpha\beta} - n^\alpha n^\beta\right) \\ -\psi\left[\alpha\gamma\Gamma^i_{\alpha\beta}\left({c_h}^2\gamma^{\alpha\beta} - n^\alpha n^\beta\right)\right] \\ \frac{1}{2}\alpha g_{\mu\nu,i}\,T^{\mu\nu} \end{pmatrix} \qquad \mathcal{S}_s \equiv \begin{pmatrix} -\alpha\gamma\kappa_\psi\psi \\ 0 \\ 0 \end{pmatrix}$$

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