The role of magnetic fields in relativistic accretion flows and supernova explosions

Matteo Bugli

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Outline

Something about me

Accretion onto compact objects
- Thick accretion disks
- Stability of accretion tori around black holes
- Numerical results

Magnetized core-collapse Supernovæ
- The general problem
- MagBurst project
- Non-dipolar magnetic topologies

The road so far. . .

The Italian period

- Master degree at *Osservatorio astrofisico di Arcetri, Firenze*
  (supervisors: Luca Del Zanna, Niccolò Bucciantini)

The German period

- PhD at *Max Planck Institut für Astrophysik, Garching*
  (supervisor: Ewald Müller)

The French period

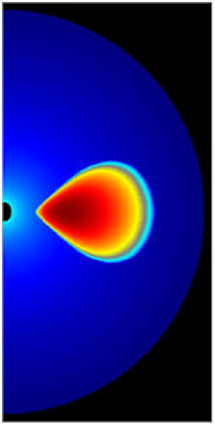
- PostDoc at *CEA in the MagBurst project (LMPA)*
  (advisor: Jérôme Guilet)

Accretion disks

- Accretion on compact objects is the central engine that powers up a list of astrophysical systems (AGNs, GRBs, X-Ray Binaries, etc...).
- It occurs almost always through a disk (conservation of angular momentum).
- Accretion ⇒ transport of angular momentum outwards ⇒ local shear stress.
- Magnetic fields play a crucial role in enabling accretion (e.g. MRI, Balbus and Hawley (1998)) and collimating relativistic outflows (Blandford and Znajek, 1977).

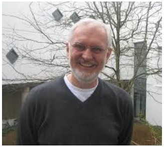
Thick disks

- Significant pressure gradients ⇒ disk supported not just by rotation.
- Sub-Keplerian angular momentum distribution, thicker and hotter than standard-model.
- Used to model accretion flows close to the black hole event horizon.
- Difficult to resolve the scales where turbulence and dissipation occur, for which local models work better.



(Gammie et al., 2003)

3D tori and the PPI-MRI interaction



Ewald Müller

Pedro J. Montero

Jérôme Guilet

Luca Del Zanna

Niccoló Bucciantini

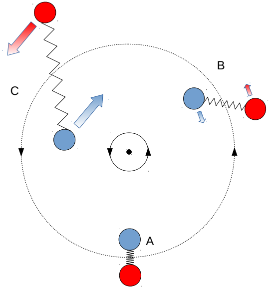
Magnetorotational instability

- Disks are hydrodynamically stable by the *Rayleigh stability criterion*

$$\frac{d(R^4\Omega^2)}{dR} > 0$$

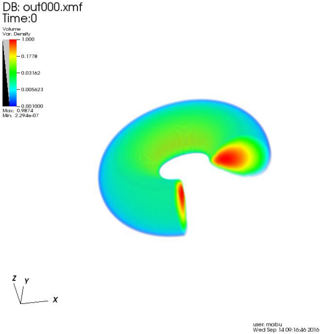
- But they are MHD unstable when (Balbus and Hawley, 1998)

$$\frac{d(\Omega^2)}{dR} < 0$$

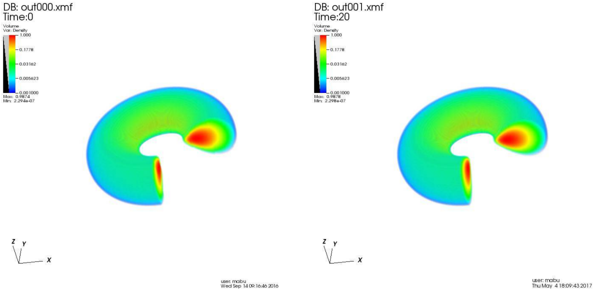


- Local instability
- Linear instability (normal mode analysis)
- Independent of field strength and orientation
- Grows on dynamical time scales

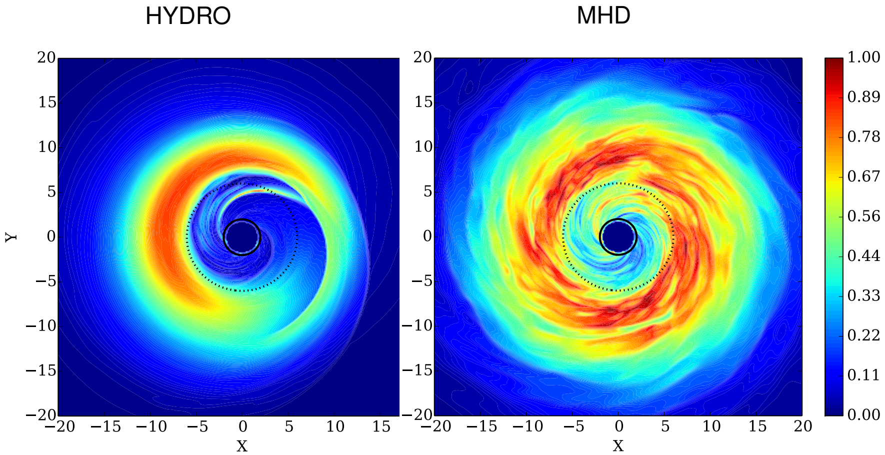
Papaloizou-Pringle instability (PPI)



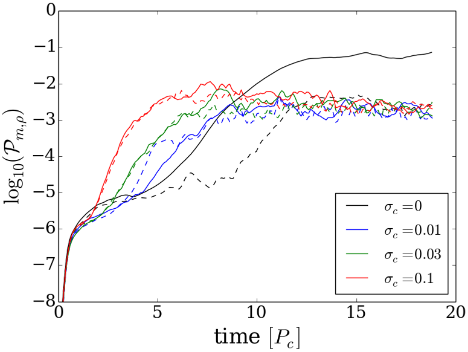
3D simulations with ECHO (Bugli et al., 2018)



Equatorial density slices



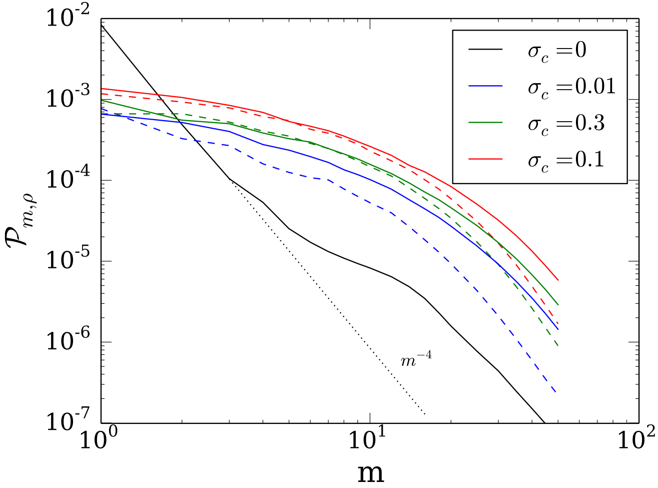
Azimuthal modes power



$$\mathcal{P}_{m,\rho} = \left\| \frac{1}{2\pi} \int_0^{2\pi} \rho e^{im\phi} \mathrm{d}\phi \right\|^2$$

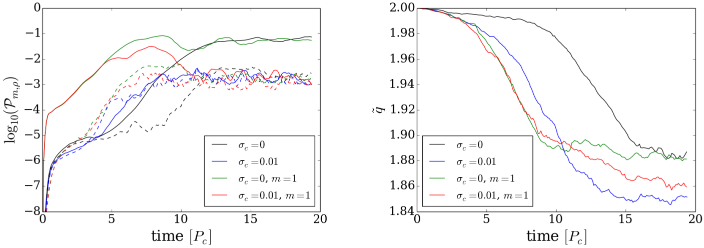
- Solid $\Rightarrow m = 1$
- Dashed $\Rightarrow m = 2$
- P_c: central orbital period
- σ_c: central magnetization

Density Spectrum



What if the PPI has an initial "upper hand"?

- Initial $m = 1$ perturbation in the orbital velocity
- Transient growth of the PPI, then the $m = 1$ mode is damped
- No clear deviation in the angular momentum profile (Hawley, 2000)
- $\Omega \propto R^{-\tilde{q}}$, with $1.5 < \tilde{q} < 2$



Conclusions (I)

PPI vs. MRI

- General suppression of the $m = 1$ mode selected by PPI.
- Possible transient growth of the PPI, followed by a damping due to the coupling with higher order modes.

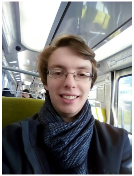
Further aspects to be considered:

- Test more general magnetized equilibrium solutions (Gimeno-Soler and Font, 2017).
- Magnetic diffusion could allow for a significant growth of the $m = 1$ mode.
- Inclusion of the disk's self-gravity could significantly affect the suppression of PPI (Mewes et al., 2016).
- Computation of GW signatures of the interplay between PPI and MRI (Kiuchi et al., 2011).

Magnetized core-collapse Supernovæ

Raphaël Raynaud

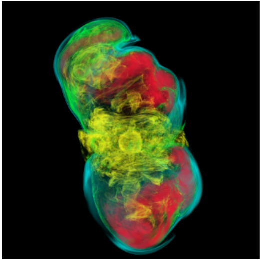
Jérôme Guilet



Alexis Reboul-Salze

CCSN: a simplistic introduction

- Core-collapse supernova:
  - gravitational collapse of a massive star out of nuclear fuel
  - shock formation when nuclear densities are reached
  - expansion of the shock and launch of unbound material in the ISM (explosion)
- Vast majority of CCSN explosions are understood as driven by the neutrino-heating mechanism.

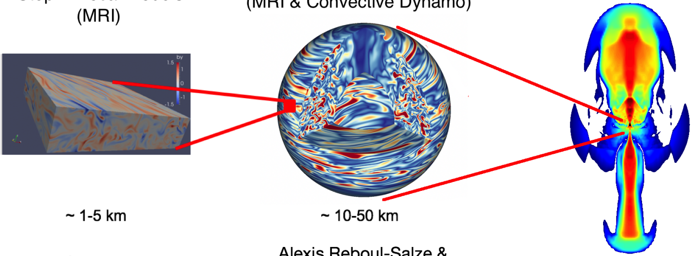


Mösta et al. (2014)

CCSN and magnetic fields

- Some classes of CCSN exhibit higher kinetic energies (Hypernovæ$\sim 10^{52}$ ergs) or luminosities (Superluminous SN $\sim 10^{51}$ ergs)
- Rotation and magnetic fields can provide an important energy reservoir
- Amplification of the field to dynamically significant strength (core compression, winding of poloidal field, MRI. . .)

The MagBurst project



Step 1: Local models
(MRI)

Step 2: Global models
(MRI & Convective Dynamo)

Step 3: Hypernova

~ 1-5 km

~ 10-50 km

Jérôme Guilet

Alexis Reboul-Salze &
Raphaël Raynaud

Matteo Bugli

- Amplification of magnetic field and magnetar formation
- Multi-scale problem, interconnected steps
- How does the PNS dynamo affect the explosion properties?

Initial magnetic field: pure dipole?

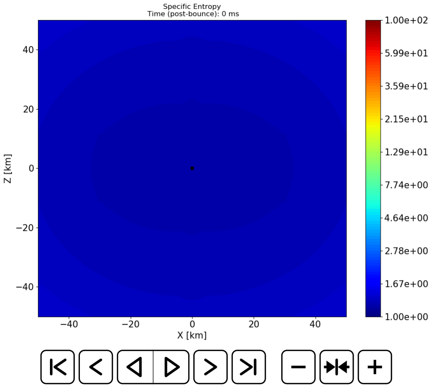
- Poor constraints from both observations and evolutionary models on the initial field.
- Uniform field up to $r_0 \sim 10^3$km, then magnetic dipole (Suwa et al., 2007):

$$A_\phi = \frac{B_0}{2}\frac{r_0^3}{r^3 + r_0^3} r \sin\theta$$

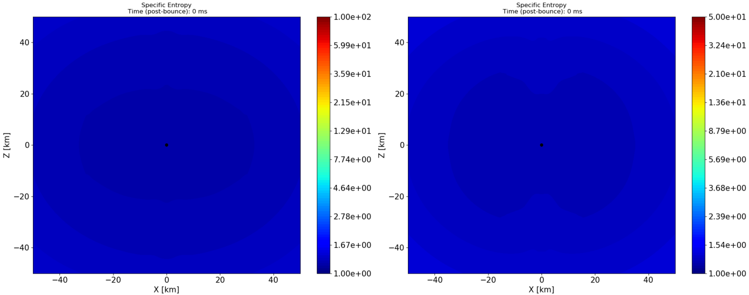
- Very few examples of quadrupolar field in the literature (Ardeljan et al., 2005; Sawai et al., 2005) with somewhat contradicting results.
- Generalized multipolar expansion:

$$A_{\phi,l} = B_0 \frac{\sqrt{l}}{2l+1}\frac{r_0^{l+2}}{r^{l+2}+r_0^{l+2}} r \frac{P_{l-1}(\cos\theta) - P_{l+1}(\cos\theta)}{\sin\theta}$$

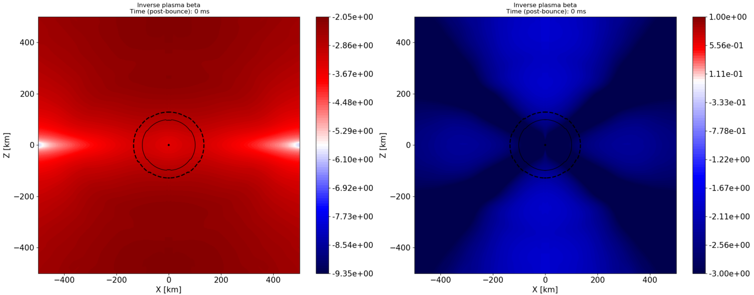
Standard magnetorotational explosion



Dipole vs. Quadrupole (preliminary!)



Dipole vs. Quadrupole (preliminary!)



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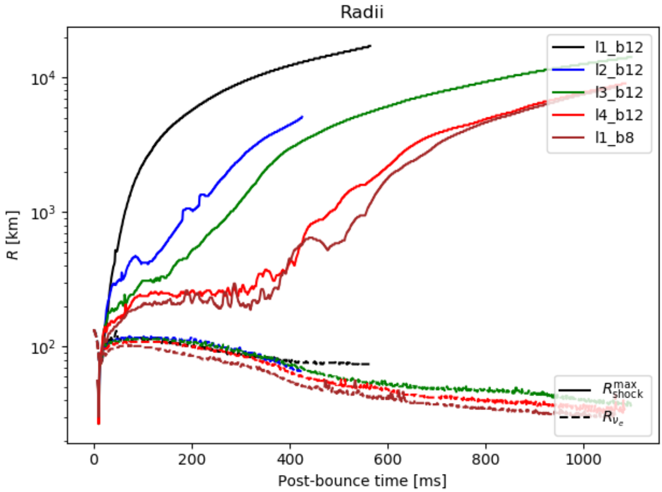
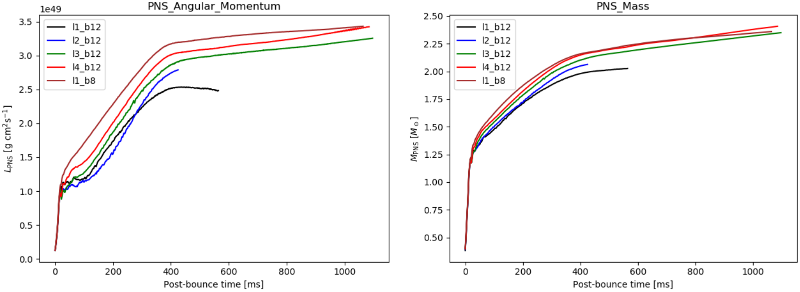
Comparison: shock radii (preliminary!)



Comparison: PNS mass and spin (preliminary!)



Conclusions (II)

- Impact of different multipolar configurations on the onset of explosion, PNS mass accretion and spin evolution.
- Later explosions and higher mass and spin of the PNS for higher multipoles.

Perspectives

- Extension to 3D using the axisymmetric models as guiding line
- Subgrid modeling of the unresolved dynamo in the PNS (mean-field approach)

Merci pour votre attention!

References I

Ardeljan, N. V., Bisnovatyi-Kogan, G. S., and Moiseenko, S. G. (2005). Magnetorotational supernovae. *Monthly Notices of the Royal Astronomical Society*, 359(1):333.

Balbus, S. A. and Hawley, J. F. (1998). Instability, turbulence, and enhanced transport in accretion disks. *Rev. Mod. Phys.*, 70(1):53.

Blandford, R. D. and Znajek, R. L. (1977). Electromagnetic extraction of energy from Kerr black holes. *mnras*, 179:433–456.

Bugli, M., Guilet, J., Müller, E., Del Zanna, L., Bucciantini, N., and Montero, P. J. (2018). Papaloizou-Pringle instability suppression by the magnetorotational instability in relativistic accretion discs. *Monthly Notices of the Royal Astronomical Society*, 475:108–120.

De Villiers, J.-P., Hawley, J. F., Krolik, J. H., and Hirose, S. (2005). Magnetically Driven Accretion in the Kerr Metric. III. Unbound Outflows. *apj*, 620:878–888.

References II

Gammie, C. F., McKinney, J. C., and Tóth, G. (2003). HARM: A Numerical Scheme for General Relativistic Magnetohydrodynamics. *apj*, 589:444–457.

Gimeno-Soler, S. and Font, J. A. (2017). Magnetised Polish doughnuts revisited. *Astronomy & Astrophysics*, 607:A68.

Hawley, J. F. (2000). Global Magnetohydrodynamical Simulations of Accretion Tori. *ApJ*, 528(1):462.

Kiuchi, K., Shibata, M., Montero, P. J., and Font, J. A. (2011). Gravitational Waves from the Papaloizou-Pringle Instability in Black-Hole-Torus Systems. *Physical Review Letters*, 106(25).

McKinney, J. C. and Blandford, R. D. (2009). Stability of relativistic jets from rotating, accreting black holes via fully three-dimensional magnetohydrodynamic simulations. *mnras*, 394:L126–L130.

References III

Mewes, V., Font, J. A., Galeazzi, F., Montero, P. J., and Stergioulas, N. (2016). Numerical relativity simulations of thick accretion disks around tilted Kerr black holes. *prd*, 93(6):064055.

Mösta, P., Richers, S., Ott, C. D., Haas, R., Piro, A. L., Boydstun, K., Abdikamalov, E., Reisswig, C., and Schnetter, E. (2014). Magnetorotational Core-collapse Supernovae in Three Dimensions. *The Astrophysical Journal*, 785(2):L29.

Palenzuela, C., Lehner, L., Reula, O., and Rezzolla, L. (2009). Beyond ideal MHD: Towards a more realistic modelling of relativistic astrophysical plasmas. *mnras*, 394:1727–1740.

Sawai, H., Kotake, K., and Yamada, S. (2005). Core-Collapse Supernovae with Nonuniform Magnetic Fields. *The Astrophysical Journal*, 631(1):446.

References IV

Suwa, Y., Takiwaki, T., Kotake, K., and Sato, K. (2007). Magnetorotational Collapse of Population III Stars. *Publications of the Astronomical Society of Japan*, 59(4):771–785.

Wielgus, M., Fragile, P. C., Wang, Z., and Wilson, J. (2015). Local stability of strongly magnetized black hole tori. *Monthly Notices of the Royal Astronomical Society*, 447(4):3593–3601.

Woosley, S. E. and Heger, A. (2006). The Progenitor Stars of Gamma-Ray Bursts. *The Astrophysical Journal*, 637(2):914.