Description scientifique du projet

• Titre du projet : **GR-MHD simulations of accretion-ejection flows in the close vicinity of compact objects**

• Numéro du projet DARI[1] : [Numéro de projet]

• Responsable scientifique[2] (nom, prénom) : Casse Fabien

• Laboratoire : AstroParticule & Cosmologie (APC)

• Nombre d'heures demandées (Cpu mono-processeur) sur le projet :
CINES SGI ICE Jade : 100 000 heures scalaires

1 Résumé

Our group is asking for 100 000 h CPU on the parallel CINES computer 'Jade' in order to validate and then use our newly developed GR-(M)HD code devoted to study accretion-ejection phenomena around compact objects. In the past ten years we have been studying disk instabilities as models for the observed variability in compact objects. We focused at first on analytical work, then on 2D (r, ϑ) numerical simulations and, in the past few years, we have been developing 3D simulations of those accretion-ejection system, first in a purely keplerian disk, then using a pseudo-newtonian approach. In order to pursue our effort, we are now developing a GR-(M)HD setup for AMRVAC (Adaptive Mesh Refinement Versatile Advection Code) (Keppens et al. 2012). The originality of this new version of the code lies in its ability to handle any kind of metrics, thus enabling us to study exotic objects (boson stars, etc...) in addition to the standard black hole. Before the forthcoming year, we plan to finish the last tests of the GR-HD module so tha we will run massively parallel simulations to study the dynamics of accretion disks in general relativity. Once those runs are performed, we will then turn to a ray tracing code, GYOTO, implicitly parallel, to produce the light curve that we can then compare with observations.

1. Uniquement en cas de demande de prolongation d'un projet existant.
2. Le responsable se charge du suivi du projet et fournit un bilan en fin d'année.

Nom et prénom	Fonction	Etablissement
CASSE Fabien	Maître de conférences	APC
DODU Fabrice	Ingénieur de recherche	APC
EL MELLAH Ileyk	Doctorant	APC
MELIANI Zakaria	Astronome-adjoint	LUTh
VARNIERE Peggy	Chargée de recherche	APC
VINCENT Frédéric	Post-doctorant	Copernicus Astron. Center, Warsaw

TABLE 1 – Members of the collaboration

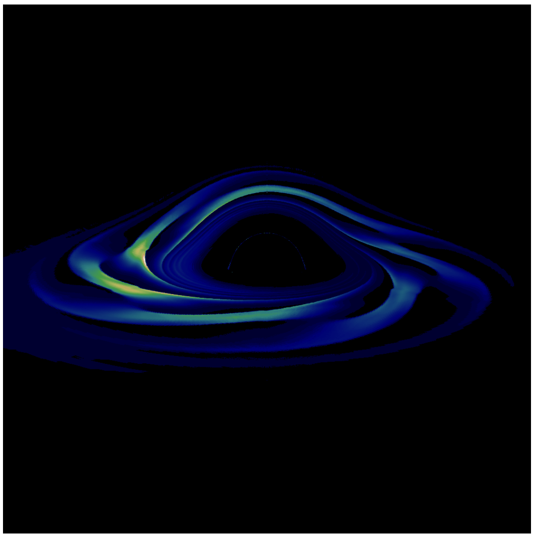
2 Présentation générale

The advent of high energy observation facilities in the last decades has proven the existence of powerful mechanisms emitting photons up to gamma-rays. It is now commonly admitted that the most energetic events are associated with compact objects believed to be relics of massive stars. These objects are prone to the most extreme gravity fields and are likely efficient attractors of the plasma present in their vicinity. The motion of plasma in the close neighborhood of compact objects is only properly described in the framework of general relativistic magnetohydrodynamic (GR-MHD). The equations governing GR-MHD are so complex that the only way to solve them is through large-scale numerical simulations. The topic of the present demand is to sustain a computational effort dedicated to GRMHD simulations of accretion flows near compact objects and to link them to synthetic observations of the associated violent events.
In the past decade only a few full GRMHD codes have emerged. GRMHD simulations were either used to describe the accretion of mass onto a black hole (Hawley 2011) or to demonstrate that an energy flux from the black hole can occur to potentially give birth to relativistic jets (McKinney et al. 2013). More recently the regime of rapidly rotating black holes is being explored (Penna et al. 2013) while ray-tracing from GR-MHD simulation is done in idealized zero-spin case (Schnittman & Krolik, submitted to ApJ). Our project will benefit from their advances while focusing more on the variability and also adding extra features such as the creation of 'numerical observation' at any spin or the integration of non-standard (tabulated) metrics.
Accretion engines share the common ingredients of a gravitating central body and a radiating, gaseous disk. This unifying picture warrants the pursuit of fundamental principles even though the inner disk and the mass accretion rate can vary significantly. In the case of black hole binaries we have another source of information in the form of variability on different timescales.

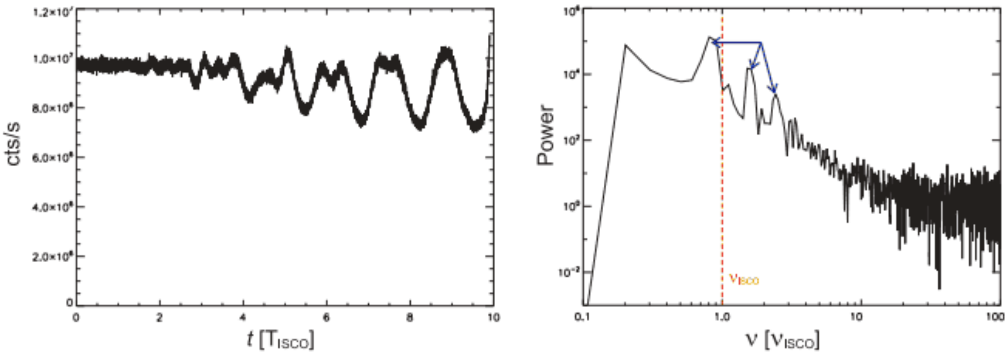
Being able to understand and explain these strong and recurrent behavior will give us access to the conditions in the accretion disk which are favorable to jet launching. Our proposed work aims toward a long term goal of explaining the wide diversity of variabilities in black hole systems within a unifying framework. In the process, we will advance the interconnections between observations and accretion disk theory by comparing the results of our numerical simulations directly to the observed data.

In the last ten years our team has been working on explaining the basic spectral states of black hole binaries using disks dominated by different forms of variability [2], and thus possibly by three forms of (Magneto)-HydroDynamic (MHD) instabilities.

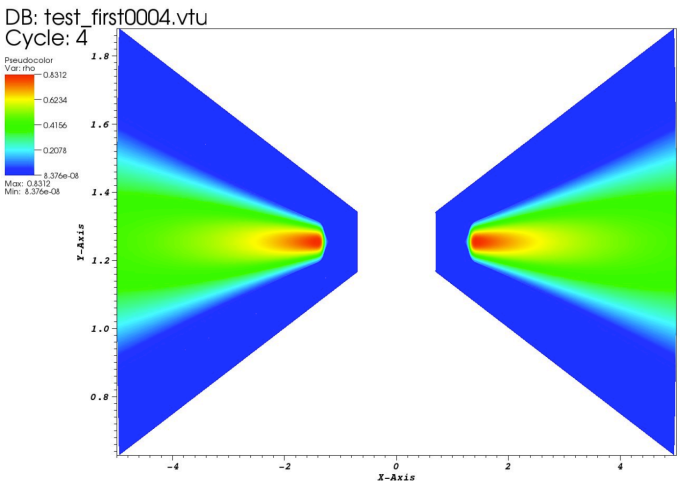
This work was done either analytically or by means of 2D (M)HD then full 3D HD simulations with a pseudo-newtonian potential mimicking GR effect near a compact objects [4]. The image on the right is an example of the output of the ray-tracing code GYOTO when coupled with the result of our pseudo-newtonian simulation. This gaves us synthetic observations and light-curve that we then ran through a detector response to simulate observations by satellites.



Below is an example of what we obtained as a study case for the LOFT satellite [5]. We ran a simulation of high-frequency variability in an accretion disk surrounding a 1000 $M_\odot$ black hole using a pseudo-newtonian potential. After using GYOTO and convoluting with the response matrix of the instrument we obtained the simulated light curve and associated power spectrum as LOFT would see it. This was done in a simplified model (no full GR) as a proof of principle.



In order to better constraint the observations we are now making the necessary transition toward using full General Relativity and not just the pseudo-newtonian approximation. We are in the process of validating a disk equilibrium in full GR-HD, for the moment with a black hole spin of zero, namely using the Schwarzschild metric.



Once our code and equilibrium is validated we will study the different responses of disk instability to the metric and its impact on the observed data. Simultaneously, we will developed an equilibrium in the case of a spinning black hole, namely using the Kerr metric. Once again, we will use the equilibrium developed in the case of a pseudo-newtonian approximation as a starting point for the full-GR equilibrium. The next steps of our project will include while continuing the development of GR-MHD will be devoted to the study of disk instabilities in the close vicinity of black holes such as the Rossby wave instability that might be a part of the answer of the temporal variability of high energy signal from X-ray binaries in our galaxy. According the actual progress of the GR-MHD version, a beginning of large scale GR-MHD simulation during 2014 is expected. such simulations will be devoted to the study of accretion-ejection flows where magnetic fields play a key role in the dynamics of the structure.

3 Méthode

3.1 Méthode numérique et justification de l'emploi de la machine demandée

AMRVAC code

The code AMRVAC is an adaptative mesh refinement code parallelized with MPI. This code was created to be used in a wide variety of physical applications that can be described by a set of conservative equations, independently of their nature (and not only fluides). Among the pre-existing physics modules there are modules to see the hydrodynamical and MHD equations in the classical or special relativity case. Several types of solver are also implemented, for example TVD Lax-Friedrich or HLL solvers.
The AMR grid structure is based on the use of sub-grids (of a few tens of cells in every dimension) in a tree architecture (octree in 3D). At each iteration the code uses an internal (Lohner's method) or user-supplied criteria to determine if a sub-grid needs to be refined, left as it is, or unrefined. The tree structure replaces each refined sub-grid by a 2^D sub-grid of the same cell-size but with the area of each cell less by a factor 2^D.

The parallelization is done with MPI and the scalability test done on 'Jade'by Z. Meliani showed an efficiency of the order of 80% on 2000 processors. This value is very close to the theoretical limit when one takes into account the I/O of the code needed to write the data. Those results of the parallelization efficiency were obtained using a test case in relativistic hydrodynamics, taking into account the propagation of shocks with Lorentz factors between 100 and 1000. The main test was done in 2D with 10 levels of AMR with a refinement ratio of 2. This allowed us to locally increase the resolution of the simulation by a factor of 218. The MPI-AMRVAC code also includes two different methods to write the data allowing a better flexibility. Indeed, MPI-AMRVAC can either use the methode MPI-II/IO or the method that consists of sending all the data from the slave node to the master node to minimise the number of processors taking part in the writing.

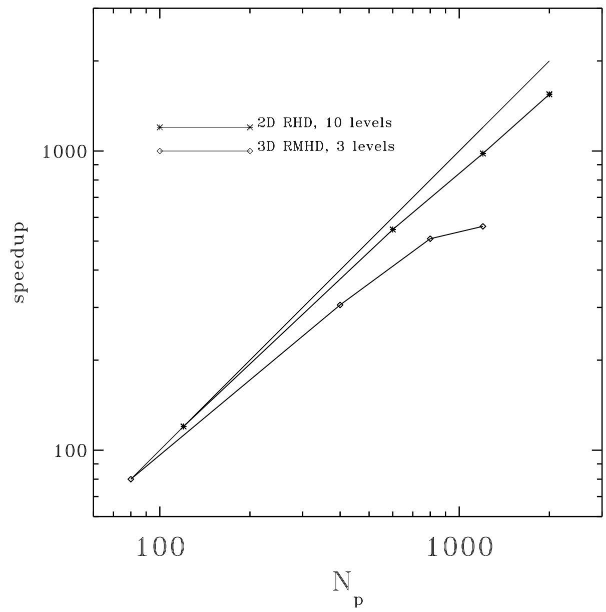


FIGURE 1 – Scaling of the MPI-AMRVAC code performed on the JADE super-computer.

GYOTO code

The General relativitY Orbit Tracer of the Observatory[3] of Paris is a ray-tracing algorithm that allows to computes the trajectories of massive and massless particles in a given metric. The final result of GYOTO can be either an image or a spectrum.

GYOTO computes the trajectory of photons backward in time from an observer's screen towards a distant astronomical target (accretion disk, star, ...). In the meanwhile, it is also capable, if needed, of integrating the geodesics followed by the massive particles that constitute the distant target. The background metric can be the Kerr metric describing rotating black holes, but GYOTO is also able to integrate geodesics in non-analytic, numerically computed metrics. As the present proposal will not use this capacity of the code, the remainder of this section assumes that the metric is Kerr. The equations of motion are solved by means of a Runge-Kutta algorithm of fourth order, with an adaptive step. The integration goes on until one of the following stop conditions is fulfilled :

- the photon reaches the emitting object,
- the photon escapes too far from the target object (what 'far' means depends of the kind of object considered),
- the photon approaches too close to the black hole's event horizon. This li-

mit is typically defined as when the photon's radial coordinate becomes only a few percent larger than the radial coordinate of the event horizon. However this limit must not be too large in order not to stop the integration of photons swirling close to the black hole before reaching the observer, thereby creating higher order images.

When imaging an optically thin astronomical target, GYOTO can integrate the radiative transfer equation inside the object, provided the emission and absorption coefficients are furnished at any point inside the object.

GYOTO is written in C++. It consists of a command line utility that allows ray-tracing a single frame, and core functionalities that are packaged in a C++ shared library, therefore easily accessible from the code. For each computation, astronomical target...) is specified through a XML file and the output image frame is stored in the astronomy standard FITS format. The GYOTO code itself is not parallel, but the ray-tracing concept is inherently parallelizable. The GYOTO command line utility is designed to split image computation in regions and can be run from standard job submission systems such as torque, thereby performing an effective parallelization.

3.2 Justification du temps

We ask for a relatively small quantity of computing time (100 000h) that will be shared between all the members of our groups since we are still in an early stage of our project and cannot foresee all issues that will have to be fixed during the GR-MHD development. This amount of computational time will allow us to perform about 30 runs on 128 processors, mainly devoted to the study of hydrodynamical accretion disks in the very close vicinity of black holes with various spin factors. We will also dedicated a part of these simulations to the study of the birth of Rossby Wave instability near the last stable orbit of the disk. The expected variability of the emission spectra (calculated with the GYOTO code) will be compared to observations from micro quasars where quasi-periodic oscillations are observed. If we make faster progress than anticipated we intend to resubmit a proposal in june 2014.

4 Bibliographie

Références

[1] R. Keppens, Z. Meliani, A.J. van Marle, P. Delmont, A. Vlasis, & B. van der Holst, 2011, JCP. Full paper, Accepted for special topical issue, with R. Keppens as Associate Editor.

[2] Varniere, P. ; Tagger, M. ; Rodriguez, J., 2011, A&A, 525, 87.

[3] F. H. Vincent, T. Paumard, E. Gourgoulhon, G. Perrin, 2011, accepted by Class. Quantum Grav., "GYOTO : a new general relativistic ray-tracing code". [gr-qc/1109.4769]

[4] F. H. Vincent, H. Meheut, P. Varniere, T. Paumard, A&A, 551, A54.

[5] F. H. Vincent, P. Varniere, H. M eheut, T. Paumard, G. Torok & M. Wildner, Proceedings SF2A Conference, 2013.