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Visualizing astrophysics simulations
New results of the COAST project

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ABSTRACT

The COAST project at CEA/IRFU at Saclay involves astrophysicists and software engineers developing simulation codes in magneto-hydrodynamics and generic tools for data structuration and visualization. Thanks to the new generation of massively parallel mainframes, computing in astrophysics had made huge progress, generating more complexity and much bigger size of numerical simulations. Two software tools have been developed at IRFU for the visualization of massive amounts of data produced by these simulation codes. SDvision is a code deployed in the framework of IDL Object Graphics, to process all results from different simulation codes developed by astrophysicists. PyMSES is a set of Python modules especially optimized for visualizing the complex data produced by our AMR simulation code RAMSES. These codes are suitable for interactive and immersive navigation for the analysis of 3D results and also for videos and stereoscopic movies productions for people at large. In this paper, we present visualizations of recent numerical simulations in astrophysics, more specifically in the domain of Interstellar Medium and Galaxies Formation.

Keywords

Astrophysics, visualization

1. INTRODUCTION

The COAST (for COmputational ASTrophysics) project [Coa00a] is a program of massively parallel numerical simulations in astrophysics, mixing astrophysicists and software engineers of CEA/IRFU institute. The COAST team is developing 3D magneto-hydrodynamics codes suitable for studying different scales of the Universe. The scientific objective is the understanding of the formation of structures in the Universe, including the study of large-scale cosmological structures and galaxy formation.

Due to the complexity, the geometry or the size of the simulations, the codes are using different numerical techniques, regular Cartesian meshes or structures such as Adaptive Mesh Refinement, spherical coordinates or multi-meshes embedded in the geometry.

The post-treatment software, and in particular the visualizing software tools, must fulfil all these requirements, so two general visualization codes have been developed inside the COAST team: the SDvision code [Pom08b] [SDv00a] , a general tool based on the IDL framework [IDL00a] and PyMSES [Pym00a], a set of Python modules dedicated to the reading and the analysis of our RAMSES AMR code data [Ram00a]. These codes are presented in this paper, with recent examples of use in the domain of interstellar medium and galaxies formation.

2. THE COAST PROJECT

The CEA/IRFU project COAST or Computational Astrophysics [Tho09a] was created in 2005 and includes all the modeling teams of Astrophysics Department; it aims to develop intensive numerical simulations in astrophysics and the generated data post-treatment.
Thanks to the complementarity of its teams, the COAST project will actually complete coverage of astrophysical topics ranging from the formation and evolution of galaxies up to those stars and planets. The COAST project already has to his credit numerous scientific achievements, but also

algorithmic knowledge dissemination. Multiple codes were in fact developed in COAST. This is for example the case of RAMSES code now widely used for the study of various astrophysical themes in the world.

The ASH, HERACLES and FARGO codes that allow us to model stellar streams, respectively radiative flows and the protoplanetary accretion disks are other examples of codes developed by the COAST teams. In addition, major efforts have been made for viewing and disseminating the results to the public. Visualization software was developed and allowed the realization of many films from the simulation results.

Specifically, films combining 3-D simulations ranging from the formation of galaxies at large scales to stellar magnetism and retracing the major stages of structure formation in the universe were produced and widely disseminated.

3. VISUALIZATION OF COAST DATA

The interactive visualization of the complex and massive three-dimensional simulations data is a challenge; the goal is to be able to visualize all data produced by different codes with similarities (written in Fortran90 and parallelized with MPI and OpenMP) and differences (regular Cartesian meshes, spherical coordinates, Adaptive Mesh Refinement structures or multi-meshes embedded in the geometry). The choice was to start from scratch, writing our own visualizing tools [Pom08a], instead of using existing codes like Paraview[Par00a] or Visit [Vis00a]. We start developing the code SDvision in the framework of the IDL Objects Graphics language, about 100000 lines written now, in order to analyze results with the physicists and provide videos in 2D or 3D stereoscopic. Objects including different data can be displayed in the same image, visualizing scalar fields (e.g. density or temperature), vector fields (e.g. velocity or magnetic field) and point clouds (e.g. dark matter). The graphics objects can be coupled with GLSL (OpenGL Shading Language) shaders algorithms to perform scientific computation and visualization by graphics card for time saving. The favored data structure for scalar and vector fields is the uniform grid. More sophisticated data structures such as AMR (Adaptive Mesh Refinement) are handled by projection onto uniform grid. The PyMSES python modules has been developed with the specific objective to visualize the AMR (Adaptive Mesh Refinement) data structures produced by the RAMSES MagnetoHydroDynamics and simulation code, used e.g. for cosmology . It offers two highly efficient CPU-intensive volume rendering algorithms: a ray-casting volume reconstruction based on direct propagation of the rays through the AMR structure, and a splatting algorithm, based on the application of a predefined texture on each cell of the AMR tree. This visualization tool offers both an interactive mode and a batch mode to produce sequence of images for videos.

Our visualization tools have been also used for the treatment of simulated data in other domains of physics, such as visualization of turbulences in the ITER plasma [Gra07a] or particles beam movement in the IFMIF accelerator [Tho14a]. Using the very same algorithms and expertise gained in the context of HPC simulations, the SDvision code was also developed in order to visualize observational astrophysical data, specially catalogs of peculiar velocities of galaxies used as input to a Wiener Filter reconstruction algorithm [Cou13a]. This algorithm produces as output the three-dimensional velocity field of gravitational origin in which matter (galaxies and dark matter) is flowing. This study led to the identification of the nature and extent of our Home supercluster Laniakea [Tul14a].

4. THE AMR CODE RAMSES

RAMSES [Tey02a] was developed in Saclay to study large scale structures and galaxies formation. It is now a rather flexible package to be used for general purpose simulations in self-gravitating fluid dynamics. It is written in Fortran 90 with extensive use of the MPI library. It is a free software for non-commercial use only. This code is a grid-based hydro solver with adaptive mesh refinement. As opposed to "patch-based AMR", cells are refined on a cell by cell basis: it is therefore called a "tree-based AMR". A very simple interface can be used to specify runtime parameters. A few routines can be modified to set more complex initial or boundary conditions.

RAMSES calculates the interaction of Dark Matter with baryonic gas, resolving the equations of magneto-hydrodynamics and gravitation. The code is used worldwide by the community of astrophysicists.

5. THE PYMSES CODE

The PyMSES code was written in the last five years to provide a quick and easy way of getting the data out of RAMSES simulation outputs. It is a set of Python modules which helps users analyse and manipulate very large simulations, without worrying more than needed about domain decompositions, memory management, etc… PyMSES is interfaced with a lot of powerful Python libraries (Numpy/Scipy, Matplotlib, PIL, HDF5/PyTables) and can be used with existing users code, as a postprocessing toolbox for data analysis. Optimization comes from a parallelized reading of the AMR data and the import of a sub-set of data corresponding to the restricted domain to visualize.

PyMSES is not an interactive environment but it provides an AMRViewer graphical user interface (GUI) module to look quickly at the AMR data. (Figure 1)

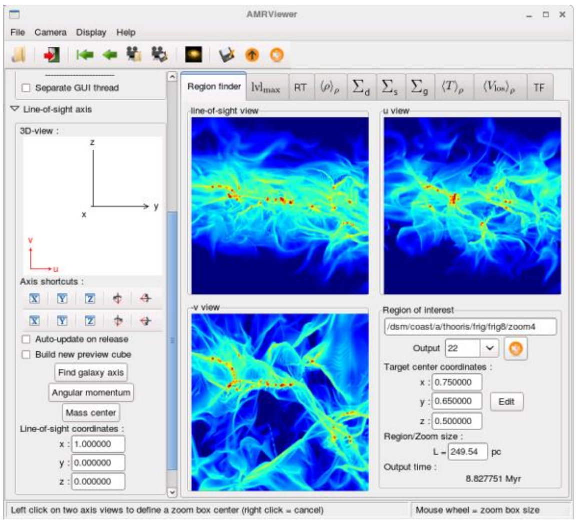

Figure 1. A view of the AMR viewer, graphical module interface of PyMSES, allowing a quick and easy look to the AMR data

6. TWO EXAMPLES OF VISUALIZATION WITH PYMSES

Visualization of Interstellar Medium

Understanding star formation is one of the major challenges of modern astrophysics. Determinant aspects of star formation haven't been yet fully unveiled because star formation is governed by the interstellar cycle, which entails: a huge range of spatial and temporal scales and a broad diversity of coupled physical phenomena such as turbulence, magnetic field, gravity and radiation.

A very recent simulation [Hen12a] has been performed on Curie, the 80000 cores, 1.5 Pflops, Hybrid CPU/GPU PRACE supercomputer at CEA computing center, using 15 million hours calculation. This simulation is including supernovae explosions, which drive the interstellar turbulence and stratification by gravity. In these simulations, dense structures develop and collapse under the influence of large scale turbulence and gravity. (Fig. 2 and 3)

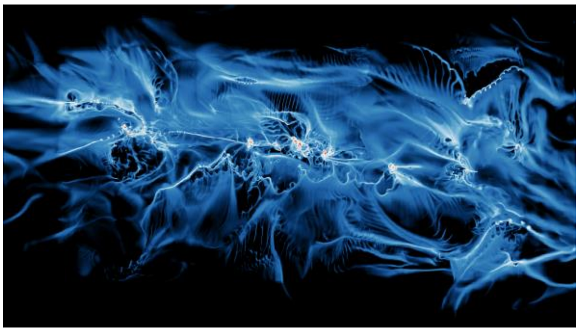

Figure 2. A visualization of a RAMSES simulation of turbulences in the Interstellar Medium; data are coming from the level 12 of the AMR mesh

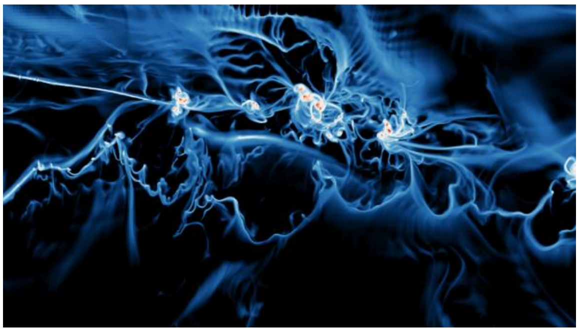

Figure 3. Same simulation as in Fig. 2; zoom using the level 15 of the AMR mesh

Visualization of Galaxies

Another very recent simulation [Roo15a] performed on the Curie supercomputer, realized in 11 million hours of computation and using the RAMSES AMR code is dedicated to star-forming galaxy studies; these are high-resolution simulations[Bou10a] [Cha10a] of star-forming disk galaxies including stellar and AGN (Active Galactic Nucleus) feedback, and it studies particularly the physical origins galactic outflows. The main novelty of this project is to account for all kinds and sources of feedback listed above simultaneously, and follow the galaxy evolution at high resolution over an extended period of time, to really understand the physical origins of galactic outflows and what their main driving mechanisms are. (Fig. 4 and 5)

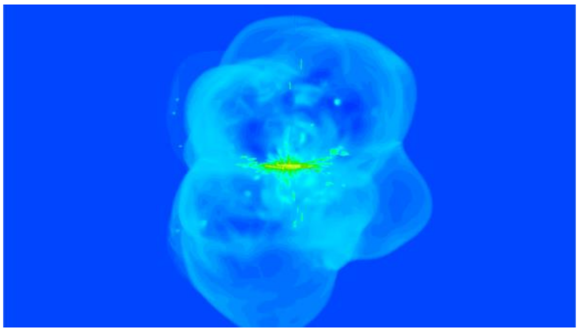

Figure 4. A visualization of a RAMSES simulation of star-forming galaxy; data are coming from the level 11 of the AMR mesh

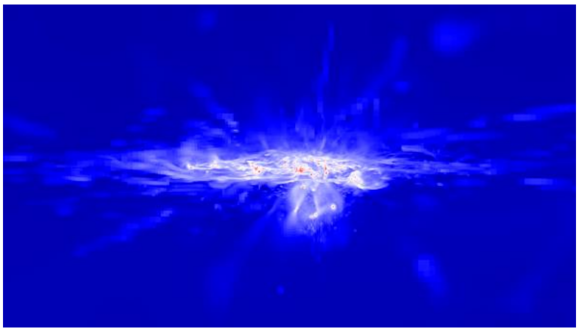

Figure 5. Zoom in a visualization of a RAMSES simulation of star-forming galaxy; data are coming from the level 18 of the AMR mesh

7. CONCLUSION

Thanks to the IDL widget SDvision developed at Saclay, the COAST team could analyze all the data provided by the astrophysicists simulation codes, using volume rendering or isosurfaces techniques. Due to the bigger and bigger amount of data coming from the latest simulations on the PRACE supercomputers in Europe, and the complexity of the data structures in an octree-based AMR code, the development of the PyMSES code was also a very useful work. Even if PyMSES has restricted functionalities (volume rendering only), his powerful capacity of AMR data reading with PYTHON modules provide us a high efficiency to analyze the results and achieve their visualization at the end of calculations. Images, videos and stereoscopic movies are also used to show our laboratory research results to the outside world; videos generated by the PyMSES code have been screened in exhibitions for the general public.

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