Research Proposal for a Master Thesis in Physics

Verifying the VPH scheme in Galaxy Formation

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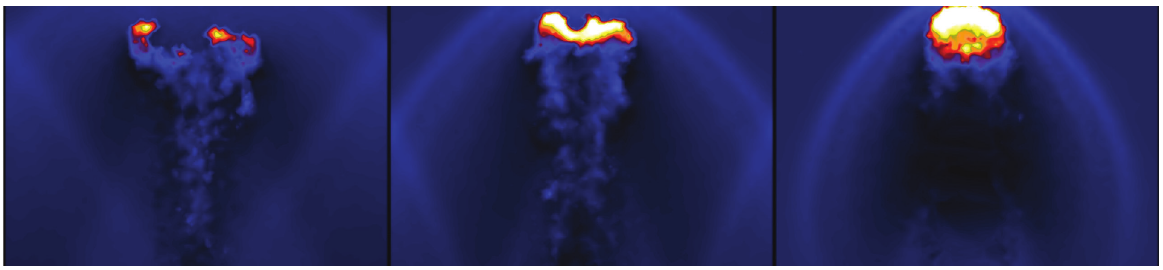

Time evolution of a gas cloud in a supersonic wind using a VPH scheme. Taken from (Heß & Springel, 2010)

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1 General Information

Information of the Student

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More detailed information of the applicant can be found here `http://goo.gl/BPZGzK`

Information of the Project

Title	**Verifying the VPH scheme in Galaxy Formation**
Field	Cosmology, Astrophysics, Physical Sciences
Advisor 1	Professor Juan Carlos Munoz-Cuartas. Universidad de Antioquia, Colombia.
University	Universidad de Antioquia, Master of Physics program
Time Frame	2 years

2 Abstract

3 Introduction

As we understand more deeply the physical processes involved in astrophysical phenomena, it becomes necessary to compute complex interactions of a ever increasing number of single components. Some prominent examples include the large-scale Universe, galaxy evolution, stellar interior, star formation and protoplanetary disk dynamics. A common aspect of these examples is that all of them can be regarded basically as a fluid mechanic problem.

Although the development of analytical approaches has demonstrated to be a valuable resource for studying these processes, their increasing complexity makes necessary to invoke numerical solutions as a more feasible alternative. For this purpose, two different families of hydrodynamics solvers has been explored and widely used by the astrophysical community. First, a family of moving-mesh-based techniques (e.g. *Smoothed Particle Hydrodynamics* `SPH` (Monaghan, 1992), *Voronoi Particle Hydrodynamics* `VPH` (Heß & Springel, 2010)), and a second family of fixed-mesh-based techniques (e.g. *Adaptive Mesh Refinement* `AMR` (Berger & Colella, 1989)).

Due to the Lagrangian character of moving-mesh methods, techniques like `SPH` are easily implemented on a computer. Furthermore, as the physical system evolves, the mass particles naturally move into higher density regions, providing a self-adjusting spatial resolution. Nevertheless, `SPH` has been shown to produce spurious suppression of fluid instabilities due to its kernel-based density estimator, making it unsuitable to model some of the dynamics accurately. On the other hand, fixed-mesh methods like `AMR` are more efficient for capturing shock dynamics. However, due to the conservative nature of the hydrodynamical equations, a fixed mesh causes a lack of Galilean invariance. Furthermore, the sampling of physical properties over the grid introduces spurious vorticity to the fluid, making this technique poor suitable for studying turbulent flows.

A completely new approach to solve hydrodynamical problems was introduced by Springel (2010) and implemented into the `AREPO` code. It combines the strengths of `AMR` and `SPH` but overcomes many of their weaknesses, hence it can be though as a mixed technique. `AREPO` uses a moving mesh based on a Voronoi tessellation defined over a set of particles that represents the fluid. The geometry of the mesh resembles very closely that of the point distribution, retaining the self-adaptivity inherent of `SPH` and also keeping a grid to capture shocks like `AMR` does. These features make `AREPO` highly accurate for simulating a wide range of hydrodynamical problems. Nevertheless, there is a price to pay for this accuracy, `AREPO` demands a huge computing time as compared with `SPH` and even `AMR`.

A very interesting alternative was introduced by Heß & Springel (2010), i.e. the *Voronoi Particle Hydrodynamics* `VPH` technique. This approach consists of an implementation of `SPH` with a modified density estimator based on the *Voronoi Tessellation Field Estimator* `VTFE`. The new estimator has demonstrated to improve substantially the spurious suppression of fluid instabilities as well as retaining the computational efficiency of the original formulation.

Finally, galaxy evolution and large-scale structure formation are very rich astrophysical scenarios where a plethora of hydrodynamical processes can be found and studied. In this fashion, cosmological simulations are quite suitable for performing detailed physical and computational comparisons of all above-mentioned techniques. It is especially interesting to quantify the computational performance of the `VPH` technique in terms of its physical accuracy as compared with the classic approaches and `AREPO`.

4 Objectives

General Objective

Quantifying the computational performance of the `VPH` technique in terms of its physical accuracy for a cosmological setup.

Specific Objectives

- Evaluating the physical accuracy provided by `VPH` for a cosmological setup as compared with `AMR`, `SPH` and `AREPO`.
- Exploring and quantifying the differences between `VPH` and `AMR` for describing shock dynamics in specific hydrodynamical instabilities.
- Exploring and quantifying the differences of `VPH` and `SPH` for describing turbulent flows.
- Measuring the computational performance of `VPH` as compared with `AREPO`.

5 Theoretical Framework

6 Methodology

The proposed project is subject to a M.Sc. study and will cover the following steps:

✓ *First, a bibliographic review of the original papers of the discussed methods will be done. Also a review of previous comparison projects.*

Before carrying out our enterprise in quantifying the performance of `VPH` over cosmological setups, it is necessary to understand deeply the foundations of the classic approaches. At this point, a detailed bibliographic review of the original papers (for `SPH`, `AMR`, `VPH` and `AREPO`) should be done. Although no previous works have been done in comparing thoroughly the performance of `VPH` with other approaches over cosmological setups, there are a plenty of comparison projects for the classic approaches and even `AREPO` over galaxy simulations and commonly used benchmark problems. This literature will have to be reviewed as well.

✓ *Second, a design of the numerical experiments should be done at this point. This includes making cosmological simulations using different techniques and if necessary, constructing and simulating specific benchmark problems.*

As this project will be entirely based on numerical results, computing a set of cosmological simulations as well as some benchmark problems is one of the key steps. For this purpose, we will use some packages like `GADGET` (Springel, 2005) for `SPH` simulations, `RAMSES` Teyssier (2002) for `AMR` and a modified version of `GADGET` for `VPH`. Other standard benchmark problems will be also simulated, e.g. the sod shock tube, Kelvin-Helmholtz instabilities, a gas cloud in a supersonic wind.

✓ *Third, a thorough analysis of the numerical results will be done.*

Once obtained the numerical results from the performed simulations, a thorough analysis of the physical accuracy of `VPH` as compared with the other techniques will be done for each situation. A computational performance analysis of the `VPH` technique will be also carried out, i.e. computing time, memory and processor usage.

✓ *Fourth, a first-author paper with the main result will be prepared.*

The more relevant results of our project will be prepared as a paper and submitted to some high impact international journal. If possible, a participation in some international event is also included in this step.

✓ *Fifth, a thesis will be written.*

A dissertation for obtaining a M.Sc. in Physics degree will be prepared. A streamlined description of each technique will be included as well as the presentation of the performed simulations and a discussion of all our results and conclusions.

7 Expected Results

At the end of the stipulated development time for this project, we hope to have obtained the following results:

- A toolbox of codes to study the performance of hydro-solvers over cosmological setups and over standard benchmark problems in fluid mechanics.

- A set of cosmological simulations computed by using each of the studied techniques.
- A M.Sc. thesis.
- Submitting a first-author paper to an international journal.
- Participating with a poster or an oral presentation in an international event.

8 Scientific Impact

The matter content of the Universe has been probed to be dominated by the dark matter component Planck Collaboration (2013). Accordingly, most of the related numerical work in cosmology and galaxy formation has been carried out based on dark matter only simulations. Nevertheless, on smaller (galactic) scales, the effects of baryons become significant. For example, recent hydrodynamical simulations show that filamentary gas accretion in early stages of galaxy evolution is a key physical process; there is evidence that it plays a central role in the formation of discs Dubois & et al. (2014), determining the alignment of galaxies with respect to the web Hahn et al. (2010) and fuelling high star formation rates Dekel et al. (2009).

These results show the importance of modelling baryons by incorporating gas dynamics into cosmological simulations. For this purpose, `AMR` and `SPH` have been widely used by the astrophysical community. However, due to the singular situations where each of those techniques fails, general purpose hydrodynamical simulations cannot be reached by means of them.

The recently developed approach `AREPO` Springel (2010) has demonstrated to be highly efficient dealing with some of the most critical weaknesses of `AMR` and `SPH`, what makes it a very appealing alternative. However, its demanding computing time also makes it infeasible when computational resources are rather limited. In this direction, our endeavour in quantifying the computational performance and the improved physical accuracy of `VPH` would contribute with valuable insight of this technique as a more feasible option when limited computational resources are available.

9 Schedule

Next it is shown a table with the proposed activities scheduled for each term of the project.

Goals	**Term I**	**Term II**	**Term III**	**Term IV**
Bibliographic review	X			
Numerical experiments	X	X		
Analysis of results		X	X	
International journal paper			X	
Dissertation				X

Table 1: Terms range from 2014-02 for term I, up to 2016-01 for term IV.

8 Bibliography

Berger M. J., Colella P., 1989, Journal of Computational Physics, 82, 64

Dekel A., Birnboim Y., Engel G., Freundlich J., Goerdt T., Mumcuoglu M., Neistein E., Pichon C., Teyssier R., Zinger E., 2009, Nature, 457, 451

Dubois Y., et al. 2014, ArXiv e-prints

Hahn O., Teyssier R., Carollo C. M., 2010, MNRAS, 405, 274

Heß S., Springel V., 2010, MNRAS, 406, 2289

Monaghan J. J., 1992, ARA&A, 30, 543

Planck Collaboration 2013, ArXiv e-prints

Springel V., 2005, MNRAS, 364, 1105

Springel V., 2010, MNRAS, 401, 791

Teyssier R., 2002, A&A, 385, 337