Research Proposal for DAAD PhD scholarship
The Gaseous Cosmic Web with AREPO

Sebastian Bustamante Jaramillo

A projection of the cosmic web in the ILLUSTRIS simulation, that was made with AREPO (http://www.illustris-project.org/)

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1 General Information

Information of the Applicant

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

Information of the Project

Title	**The Gaseous Cosmic Web with AREPO**
Field	Cosmology, Astrophysics, Physical Sciences
Advisor 1	Volker Springel, PhD. Heidelberg Institute for Theoretical Studies (HITS) & University of Heidelberg, Germany
Advisor 2	Jaime Forero-Romero, PhD. Universidad de los Andes, Colombia
University	University of Heidelberg, IMPRS PhD program
Time Frame	3 years

2 Abstract

3 Introduction

Since the filamentary nature of the large-scale matter distribution of the observable cosmos (the so-called cosmic web) was evidenced by the first compiled galaxy surveys (Chincarini & Rood, 1975; Gregory & Thompson, 1978; Einasto et al., 1980a,b; Kirshner et al., 1981, 1987), it has been identified as one of the most striking features of the Megaparsec Universe and an increasing interest in studying its dynamical properties and environmental influences on a plethora of different astrophysical phenomena has become evident. At present, a tremendous amount of observational data supports the cosmic web scenario at the point that it has become an essential part of the current standard paradigm in cosmology. Last generation galaxy redshift surveys, such as the *two-degree-Field Galaxy Redshift Survey* (2dFGRS, see Colless et al. (2001) and Colless et al. (2003)) and the *Sloan Digital Sky Survey* (SDSS, see York et al. (2000) and Abazajian et al. (2009)), do evince the intricate and complex structure of the cosmic web at a level of detail never seen before. In addition, other valuable observational resources like X-ray emissions of hot intracluster gas embedded into large clusters of galaxies, Ly-α forest absorption lines in the spectra of shock-heated neutral hydrogen gas residing in filaments and clusters, and weak gravitational lensing and imprints in the CMB field produced by foreground structures, have also validated this picture undoubtedly.

On the theoretical side, early descriptions of the evolution of the large-scale Universe, based on gravitational instabilities in primordial stages and leaded by the seminal work of Zel'dovich (1970), are highly consistent with the cosmic web picture, where planar pancake-like regions of matter enclose enormous sub-dense voids and are bordered, in turn, by thin filaments and high-density clumpy knots (Bond et al., 1996). Since then, our understanding of the structure and dynamics of the cosmic web has been dramatically improved as new and more powerful theoretical and computational tools and more refined observational data become available. In particular, N-body simulations, fuelled by last generation computing systems and ever more efficient numerical algorithms, are acquiring an increasingly important role in fathoming the complexity of the large-scale Universe.

Due to the poorly interacting (and unknown) nature of the dark matter component of the cosmic inventory, observations have been devoted to establish the underlying structure of the cosmic web entirely based on detecting baryonic matter (with the exception of non-direct inferences based on gravitational lensing). On the other hand, the highly complex *gastrophysical* processes involved in baryonic dynamics, i.e. shock heating, photoionization, supernova feedback, stellar wind, radiative cooling, star formation and others, make extremely difficult to obtain a completely consistent and reliable scenario from numerical simulations as many of these processes are not fully understood yet. Accordingly, most of the related numerical research has been made based on dark matter-only N-body simulations, where the gas dynamics has been neglected. Although this duality between observations and simulations can be thought as a complementary situation, actually it also makes quite hard to splice both, observational data and numerical predictions.

Despite the fact that most of above-mentioned *gastrophysical* processes occurring in baryonic dynamics do represent a challenge for any endeavour for simulating the large-scale Universe, the solely hydrodynamic nature of the gas has been challenging enough even for the most simplified models. Traditionally, two different hydro-solvers have been used for astrophysical and cosmological applications, i.e. a Lagrangian *Smoothed Particle Hydrodynamics* (`SPH`) technique (Monaghan, 1992) (see e.g. the `GADGET` code, Springel (2005)) and an Eulerian solver on a mesh with *Adaptive Mesh Refinement* (`AMR`) (Berger & Colella, 1989) (see e.g. the `RAMSES` code, Teyssier (2002)). `SPH` is easily implemented on a computer and due to its Lagrangian character, its usage is very suitable for many problems as the mesh follows the evolution of each single particle, with an continuously auto-adjusting resolution. However its same Lagrangian nature causes an inhomogeneous and distorted spatial resolution in simulations. This fact makes difficult to account for properties of voids in cosmological simulations and also causes suppressions in fluid instabilities, making this scheme poor suitable for capturing shock dynamics. An artificial viscosity is usually implemented for improving the accuracy in these situations. On the other hand, `AMR` is more efficient for capturing shock dynamics without any artificial term, however due to the conservative nature of the hydrodynamical equations, a fixed mesh causes a lack of Galilean invariance, making the computer implementation considerable harder than `SPH`. Furthermore, due to the unsmooth sampling of physical properties, spurious vorticity is introduced to the fluid, making the scheme unsuitable for studying turbulent flows (for a further discussion and comparison of both schemes, see Plewa (2001)).

Recently, a completely new paradigm was introduced by Springel (2010) that combines the strengths of `AMR` and `SPH` but overcoming their weaknesses, i.e. the `AREPO` code. This code is based on moving mesh built from a Voronoi tessellation defined over a set of discrete particles that represents the fluid. This procedure is highly efficient as the geometry of the mesh follows very closely that of the point distribution, avoiding in this way a distorted spatial resolution, but still retaining the auto-adaptivity inherent of the `SPH` scheme. Unlike `AMR`, the hydro-solver of `AREPO` is based on a Gudonov's scheme that guarantee the Galilean invariance and the conservative nature of the solutions. All of these features makes `AREPO` highly efficient and accurate for almost any hydrodynamical problem, including shock dynamics as well as fluid instabilities and turbulent flows, essential processes for simulating the high complexity of large-scale structure of the Universe.

4 Objectives

✓ Understanding, at the light of the last generation `AREPO` simulations, how is the dynamics of the baryonic matter component throughout the pipeline set up by the potential wells of the dark matter cosmic web.

✓ Quantifying gaseous environmental effects on galaxy formation and dynamics.

✓ Comparing our results with current (predicting new) observables and imprints of the gaseous cosmic web.

5 Methodology

The proposed project is subject to a PhD study and will cover the following aspects:

✓ *First, a set of simulations must be established for all succeeding steps. This may involve making new hydrodynamical simulations or adopting existing ones based on the `AREPO` code. This also includes a complete analysis of the simulations, i.e. characterization of physical fields (density, temperature, entropy), construction and analysis of catalogues of haloes, and others.*

As this project will be almost entirely based on numerical results, establishing a set of precise hydrodynamical simulations as a solid base for all our succeeding studies is indeed one of the key steps that must be fulfilled. The unprecedented accuracy and convergence achieved by the `AREPO` code regarding other traditionally used schemes, will guarantee the needed precision.
In Heidelberg, the required computer facilities and the access to the private code `AREPO` (of which Prof. Volker Springel is the main author) is granted. Moreover, the renowned research trajectory of Prof. Springel in numerical cosmology is certainly another appealing for pursuing this specific PhD project.

✓ *Second, a preliminary exploration of the dark matter cosmic web should be done. For this purpose, it is necessary an adaptation of some commonly used web-finding schemes (e.g. the V-web and the T-web) to the new Voronoi-based paradigm established by the `AREPO` code.*

A first exploration of the structures of the simulations should be done. For this purpose, many different schemes can be found in the literature, but taking into account the reported success of tensor-based web-finding schemes (e.g. the V-web and the T-web), in which prof. Jaime Forero-Romero has a wide research trajectory, it is quite interesting to quantify the dark matter cosmic web of last generation simulations at the light of them. Nevertheless, it is also necessary to adapt these schemes to the Voronoi-based paradigm leaded by `AREPO` as they was originally intended for more traditional *Cloud-in-Cell* methods for estimating the density field. It is also worth mentioning previous research experiences of the applicant in this topic.

✓ *Third, once established the underlying dark matter cosmic web, it is necessary to quantify the through gas dynamics. To this aim, inward and outward gas flows through potential wells (set by non-linear structures such as clusters and filaments) and accretion rates of the gas component residing within dark matter halos at different redshifts should be computed. At this point, it should be possible to evaluate environmental influences on different astrophysical phenomena.*

In order to exploit the new accuracy provided by the `AREPO` code, a correct quantification of the gas dynamics should be done. The current cosmological paradigm predicts a complex pipeline set by the potential well of non-linear structures, generally corresponding to clusters and filaments, through which the gas is transported toward over-dense regions like dark matter haloes. This process yields to different environmental phenomena of great current interest. We list here the most relevant for this project: influence of filament-induced flows on star forming galaxies at high redshifts, acquisition of the spin of galaxies through exchanging of angular momentum with the gaseous cosmic web, and kinematical and dynamical effects of the host environment on Local Group-like systems.

✓ *Finally, a detailed comparison of our potential predictions (or restrictions) with currently available observational data should be done.*

6 Current State

At present, the applicant has already the fundamental basis in Astrophysics and Cosmology required for this investigation. This can be confirmed by his research trajectory, including a paper (as co-author) published in *ApJL* in which was studied the kinematics of the Local Group in a cosmological context, and some participations in academic congresses. Furthermore, a Bachelor's thesis [1], where was numerically studied the preferred place of Local Group-like systems regarding the host environment in the cosmic web, also proves the ability of the applicant for handling simulations and massive data, a skill that is indeed necessary for carrying out this project.

Year	Goals
First	• First goal • Second goal
Second	• First goal • Second goal
Third	• First goal • Second goal

7 Timetable

8 Bibliography

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[1]Further information and an electronic version of this thesis can be found here `https://github.com/sbustamante/Thesis`.

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