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Numerical Simulations of Host Galaxies of Gamma-Ray Bursts

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1 Introduction

The research project concerns cosmological galaxy formation through investigation of the properties of host galaxies of Gamma-Ray Bursts (GRBs). The class of GRBs we are currently interested in is the so-called long-duration bursts, likely to result from the collapse of short-lived, massive stars. As a result, GRBs are potentially an excellent tracer of galaxy formation in the universe. Galaxies that host GRBs were observed for the first time in 1997 and the current sample now includes around 50 hosts, making this field a relatively new area in cosmology. Addressing the issue of the properties of GRB host galaxies makes possible comparisons with the other known sub-populations of galaxies and contributes to the understanding of galaxy evolution as well as the galaxy formation theory.

The approach we have adopted consists of using numerical simulations of cosmological galaxy formation, in which we identify host galaxies using observational information. These simulations follow in a self-consistent way the dynamical evolution of the dark matter and baryonic matter and include a model of galaxy formation, based on a heuristic approach. These simulations cannot, however, follow the large scales of the universe connected with the creation of the largest structures at the same time as the small scales where stars form. Typically the computational volume has a scale of a few tens of Mega-parsecs while typical stellar scales are measured in parsecs. Our 3-dimensional code includes gravitation, hydrodynamical shocks and radiative cooling computed without assuming ionization equilibrium. That means that the evolution of six chemical densities of the primordial plasma is followed. The dark matter is sampled with particles and an N-body method computes their displacement whereas the gas is evolved on a grid using an Eulerian method. From the gas distribution at each time-step, cold, dense, collapsing gas regions are identified. It is in such regions that galaxy formation takes place. A fraction of the identified gas is converted into stellar particles whose mass and epoch of formation are recorded. Their evolution is then treated in a non-collisional way, as is the dark matter. The stellar particles are then grouped together at different redshifts to form galaxies. The comoving size of the computational volume is 32 h^{-1}Mpc and we use 256^3 dark matter particles and an equal number of grid cells. With the physics and resolution involved, a simulation needs 13 GB of memory and around 100 hours and cannot be performed locally in Iceland. We have therefore greatly appreciated the access to the NEC-SX6 at the HLRS Computing Center. In the following we report the research activities we have conducted this last year.

2 Activity report

We have not been active users at the HLRS during the previous year, and have not performed any new simulations. We have emphasized the completion of on-going projects, that we describe below. On the other hand, our need for higher resolution cannot be satisfied with the current version of the code we have used so far. Therefore we started to familiarize ourselves with new codes, made available through our participation in the new project *HORIZON*, which federates the French numerical community involved into galaxy formation.

2.1 Observable properties of GRB host galaxies

In our previous report we described a first set of simulations that we ran on NEC-SX6, illustrated by a preliminary result in Fig. 2 in that report. The purpose was to generate ten simulated catalogs of galaxies at different redshifts, and to describe these galaxies through observable properties. The difficult part of this project had more to do with the estimation of observable properties than with the simulation itself, since we did not want to modify the galaxy formation model or include more physical processes in the simulation. We have instead concentrated on obtaining new properties to characterize the galaxy-objects.

For that we have used stellar population synthesis models. These evolutionary, complex codes, some of them being available to the community, combine stellar evolutionary theory, stellar atmosphere theory, and the stellar birth rate, based on the star formation history. In our procedure, the star formation history of a galaxy comes directly from the recording in the simulation of the formation epoch and mass of all the stellar particles, considered as homogeneous stellar populations. The stellar population synthesis (SPS) code we have chosen is *Starburst99* (Vázquez G. A. & Leitherer C. 2005 ApJ 621, 695) and although its use may be relatively straight forward, the combination of the SPS code with the results of the simulations, in addition to getting the observable properties we were interested in, took a much longer time. We conducted this analysis locally, on computer clusters. We have thus been able to discuss the properties of the overall population of simulated galaxies; these properties coming directly from the simulation or from the use of *Starburst99*.

We have then identified simulated galaxies having similar properties as a well-defined sample of ten observed GRB host galaxies. This sample is the only available where the optical star formation rate (SFR) and the ratio between the SFR and the optical luminosity are discussed. The major points of our study concern the description of the ten numerical host counterparts by a large set of properties, many of which are not provided directly by observations, and the comparison of this galaxy sub-population with the whole galaxy population at different redshifts. The results have been greatly improved from the preliminary results presented last year and lead to the conclusion that the numerical counterparts of the observed sample are galaxies belonging to the low-mass, high specific SFR galaxy population, with blue colors and recent epochs of formation. Our conclusions agree with recent results based on observations. Our study should be continued when a much larger observed sample will be available. This project has now been completed with an article that has recently been submitted for publication (Courty et al 2006).

2.2 The link between young/high specific SFR galaxies and GRB host galaxies

The second set of simulations we described in the last report concerned a joint analysis of the cosmological evolution of the properties of the baryonic matter and of the galaxy properties. For this purpose we saved numerous outputs, every 10 or 15 time-steps, to find in each galaxy catalogs the main progenitors of galaxies selected in the present-day catalog. Thus we are then able to determine the whole history of galaxies and follow the cosmological evolution of their properties. We have worked on this project this year through a statistical analysis of galaxy properties at different evolutionary stages, for the overall galaxy sample. We have confirmed that high specific SFRs are associated with the young evolutionary stages of galaxies. This might be a first step to understand better why high-redshift GRB host galaxies are often seen in Lyman-α emission. Indeed, a part of the Lyman-α emission comes from cold gas present in star-forming regions and the amount of such cold gas should be larger when galaxies are young. An article describing this result is currently in preparation.

2.3 The contribution of GRB host galaxies to the cosmic SFR

Following our idea that GRB host galaxies might be high specific SFR galaxies, we have started to investigate the contribution of GRB hosts to the total mass or cosmic SFR. The idea is to analyze the difference between the cosmic SFR for the whole galaxy population and the cosmic SFR due only to the high specific SFR galaxies. We have made a first analysis based on the same kind of simulation as described in the first section. The largest differences are seen as the redshift decreases and is an interesting result as it may show that the contribution of GRB host galaxies to the cosmic SFR is not dominant at the lowest redshifts, although their contribution is extremely useful to understand galaxy evolution. Hosts are more likely to contribute significantly to the cosmic SFR at high redshifts. However such an analysis may depend on the resolution of the simulation and a more quantitative investigation requires a high-resolution simulation, typically with a 384^3 dark matter particles and grid cells. Unfortunately such a simulation cannot be performed on NEC-SX6 with our current serial version of the code.

We have therefore turned to parallel numerical codes, that are available in the *HORIZON* collaboration. We started to work this winter with *Ramses* (Teyssier R. 2002, A&A 385, 337), a numerical code based on an Adaptive Mesh Refinement (AMR) technique allowing high spatial resolution. On the other hand a team of the *HORIZON* group has completed the parallel version of the code we have used so far. To pursue our project we may ask the HLRS to shift, if possible, a part of our computing hours to more appropriate platforms, such as the NEC Xeon EM64T cluster or the Cray Opteron cluster. In addition to help complete our project on the cosmic SFR, performing high-resolution simulations will allow us to get a larger and statistically reliable sample of galaxies at high redshift. We also plan to investigate how observable properties of GRB host galaxies evolve between high and low redshifts.

3 Ongoing project

We have recently started to work on a new project that we are developing on NEC-SX6, but should be performed with the *Ramses* code for high-resolution simulations. It concerns the global metalicity of galaxies, an issue of particular importance in the context of GRB host galaxies. They are expected to be low-metalicity galaxies, and a few observational studies tend to show this, explaining why host galaxies at low redshifts are not associated with galaxies producing stars at the highest rate. When high mass stars end their lives as supernovae, they inject heavy-elements into the interstellar medium that enrich the surrounding gas and contribute to its cooling. To reproduce this, we need to follow in the simulations the metalicity evolution of the gas and add the contribution of heavy-elements to the gas cooling rate. We have written a new version of our code, taking into account that the gas is in ionization equilibrium. The physics of a non-zero metalicity gas is very complex and we therefore need to use cooling functions tabulated from photoionized spectral codes, such as the *Cloudy* project (Ferland, G. J. et al. 1998, PASP 110, 761), assuming a gas in ionization equilibrium.

As a conclusion we would like to underline that the last year was kind of a transitional year, with most of the time spent on the completion of advanced projects. Furthermore we have been aware that the future of our projects depends on new, parallel codes. We are now working with the *Ramses* code, but are still at the learning stage. In the near future we may ask the HLRS to shift a part of our computing hours towards other platforms than the NEC-SX6, that we are still using to develop a different version of our current numerical code.