A Numerical Study of galaxy properties from cosmological simulations with star formation

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Abstract

From a set of 3d cosmological hydrodynamical simulations which incorporate a self-consistent model of the star-gas interactions, we have been able to obtain a statistically significant sample of galaxy-type halos with observational properties, like colors and luminosities. Using this data-base, we have studied general relations of galaxies, such as the Tully-Fisher relation, luminosity functions, environmental dependences, or cosmic star-formation density. The main motivation of our analysis was to investigate the influence of cosmological conditions (i.e. large-scales) and (short-scale) baryonic processes on the observational properties of the resulting numerical galaxies.

1 Introduction

Our numerical code is a combination of a Particle-Mesh (PM) Poisson solver and an Eulerian PPM hydrodynamical code. A detailed description of the N-body/hydro code and the equations governing the star-gas interactions can be found in Ref. [19] (YK³). Here we briefly summarize their main features. In our numerical model, matter is treated as a multi-phase fluid with different physical processes acting between them. The gas is treated as two separate phases, depending on its temperature: Hot Gas \((T_h > 10^4\text{K})\) and Cold Gas Clouds \((T_h < 10^4\text{K})\) from which stars are formed. In each resolution element, the amount of cold gas, \(m_{\text{cold}}\), capable of producing stars is regulated by the mass of the hot gas, \(m_{\text{hot}}\), (that can cool on the time scale \(t_{\text{cool}}\)), by the rate of forming new stable stars, and by supernovae (SN), which heat and evaporate cold gas. The supernovae formation rate is assumed to be proportional to the mass of cold gas: \(\dot{m}_{\text{SN}} = \beta m_{\text{cold}}/t_*,\) where \(t_* = 10^8\text{yr}\) is the time scale for star formation, and \(\beta\) is the fraction of mass that explode as supernovae \((\beta = 0.12\) for the Salpeter IMF). Each \(1M_\odot\) of supernovae dumps \(4.5 \times 10^{49}\) ergs of heat into the interstellar medium and evaporates a mass \(A \cdot M_\odot\) of cold gas. Small values of \(A\) imply large reheating of hot gas and small evaporation, which makes the gas to expand due to the large pressure gradients. The feedback parameter \(A\) is taken to be large \((A \sim 200)\) resulting in low efficiency of converting cold gas into stars. Chemical enrichment due to supernovae is also taken into account in the following way: We assume solar composition for the gas in regions where star formation has taken place. In regions where no stars are present, we assume that the gas has primordial composition. The gas then cools with cooling rates, \(\Lambda(T_h)\) corresponding to either primordial or solar plasmas. In order to mimic the effects of photoionization by quasars and AGNs, the gas with overdensity less than 2 was kept at a constant temperature of \(10^{3.8}\text{K}\) (see e.g. Refs [4], [13]).
2 Description of simulations

The purpose of the simulations was to obtain a sufficiently large catalog of “numerical galaxies”, permitting reliable, statistically significant comparisons with observational quantities. To this end, a set of 11 simulations were performed for each of the CDM, ΛCDM (Ω_A = 0.65), and BSI models [3]. COBE normalization was taken; baryon fractions were compatible with nucleosynthesis constraints [10] (Ω_B = 0.051 for BSI and CDM, Ω_B = 0.026 for ΛCDM).

The box size was chosen to be 5.0 Mpc, but with different Hubble constants given by \( h = 0.7 \) for the ΛCDM model and \( h = 0.5 \) for the CDM and BSI simulations. The simulations were performed at the CEPBA (Centro Europeo de Paralelismo de Barcelona) with \( 128^3 \) particles and cells (i.e., 39 kpc cell width). Effects of resolution have been checked by re-running 2 of the simulations with \( 256^3 \) cells and particles. It did not result in significant changes in global parameters (mass, luminosity) of galaxies. To test the effects of supernovae feedback on the final observational properties of galactic halos, we have rerun 6 of the 11 simulations for each cosmological model, with different feedback parameter: \( A = 50 \), (strong gas reheating) and \( A = \beta = 0 \), (no reheating or mass transfer). A detailed analysis of these simulations can be found elsewhere ([3]-[4]).

More recently, we have completed a ΛCDM simulation with \( 300^3 \) particles in a 12 Mpc box (i.e. same resolution than in a 5 Mpc box). This simulation was done to check for possible effects due to the lack of long wavelengths in the initial power spectrum.

3 Results

From the database of galaxy-type halos extracted from the abovementioned simulations we have studied the Tully-Fisher (TF) relation in different bands (B, R, I) as well as the luminosity function in B and K [3].

The luminosity functions in the B and K bands are quite sensitive to supernova feedback. We find that the slope of the faint end \( (-18 \leq M_B \leq -15) \) of the B-band luminosity function is \( \alpha \approx -1.5 \) to \(-1.9 \). This slope is steeper than the Stromlo-APM estimate, but in rough agreement with the recent ESO Slice Project [20]. The galaxy catalogs derived from our hydrodynamic simulations lead to an acceptably small scatter in the theoretical TF relation amounting to \( \Delta M = 0.2 - 0.4 \) in the I band, and increasing by 0.1 magnitude from the I-band to the B-band. Our results give strong evidence that the tightness of the TF relation cannot be attributed to supernova feedback alone. However, although eliminating supernova feedback affects the scatter only moderately \( (\Delta M = 0.3 - 0.6) \), it does influence the slope of the TF relation quite sensitively. With supernova feedback, \( L \propto V_c^{3.5\alpha} \) (the exponent depending on the degree of feedback). Without it, \( L \propto V_c^2 \) as predicted by the virial theorem with constant \( M/L \) and radius independent of luminosity.

In Figure 1 we show the redshift evolution of the comoving star-formation density, \( \dot{\rho}_* \), of our simulations, together with a compilation of the most recent observational estimates (see [4], [2], [12], [15], [17], [18]) derived from the UV luminosity density, corrected from dust extinction, following Madau’s prescription [10].

In the low evolved BSI simulations, the effects of SN feedback on \( \dot{\rho}_* \) are striking at all redshifts, while in the CDM and ΛCDM simulations, feedback effects become significant only at \( z \lesssim 1 \): Simulations with SN feedback show a much sharper decline of \( \dot{\rho}_*(z) \), which is a reflection of the decline of the SFR inside the bright galactic halos at low \( z \) as a consequence of the higher temperature of the hot gas [4].

In higher normalized CDM and ΛCDM simulations, \( \dot{\rho}_*(z) \) is almost flat or slightly declining.
at $z \sim 1−5$. This is in good agreement with the recent observational data when correction from dust extinction is considered. In the $\Lambda$CDM–$A=200$ panel, we also show the $\dot{\rho}_*(z)$ computed in the 12 Mpc simulation box. As can be seen, it is consistent with the results from the 5 Mpc simulations. Moreover, they are also in fairly good agreement with estimates of $\dot{\rho}_*(z)$ computed from large-scale ($100 \, h^{-1}$Mpc) $\Lambda$CDM hydrodynamical simulations [11], with an analytical prescription for the SFR inside galactic halos.

4 Conclusions and future work

Despite the success of our model to reproduce some of the properties of real galaxies, it is nevertheless a simplified model of the complex star-gas interactions. UV photoionization and chemical enrichment are treated in a phenomenological way. These effects could be very important, and could change the evolution of the gas component. The advantage of using eulerian
PPM hydrodynamics is that it is simpler to advect metals as a new “phase” of the gas density, which would change the local cooling rates of the gas. Stars will then form with different metallicities and their luminosities can be computed by the new generation of population synthesis models. UV radiation from the stars is another important effect that has not yet been fully explored. Our purpose is to make a self-consistent modeling of the photoionization of the gas from UV flux coming from the stars generated in the simulations. This will constitute another feedback mechanism in our star-gas model.

The main goal one wants to achieve in a cosmological simulation is to resolve the internal structure of individual galaxies formed in volumes that are large enough to allow a reliable realization of the initial power spectrum. New numerical algorithms based on Adaptive Mesh Refinement (AMR) techniques are starting to be considered one of the most promising ways to pursue this goal. But higher resolution does not necessarily mean better results, unless the most important physical processes acting at the scales of interest have been included in the simulation. Our work follows this premise. On one hand it is necessary to explore many approximations to properly model the complex physics of star formation and star-gas interactions [1]. On the other hand, new AMR methods for gravity [8] and hydrodynamics [7] have already been developed. The next logical step is to put together the different pieces and build a new generation of numerical simulations to study galaxy formation from cosmological initial conditions. In this regard, the data base obtained from simulations performed with our present numerical code (YK$^3$) will be very useful as a testbed for the new models we are currently developing.

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