Numerical Simulations of Galaxy Formation: Cooling, Heating, Star Formation

Anatoly Klypin\textsuperscript{1}, Stefan Gottlöber\textsuperscript{1,2}, & Gustavo Yepes\textsuperscript{3}

\textsuperscript{1}Department of Astronomy, NMSU, Las Cruces, NM 88001
\textsuperscript{2}AIP, An der Sternwarte 16, D-14482 Potsdam, Germany
\textsuperscript{3}Departamento de Fisica Teorica C-XI, UNAM, Cantoblanco 28049, Madrid, Spain

Talk presented at the 12th Postdam Cosmology Workshop, “Large Scale Structure: Tracks and Traces”, World Scientific 1998

1 Abstract

Formation of luminous matter in the Universe is a complicated process, which includes many processes and components. It is the vastly different scales involved in the process (from star formation on few parsec scales to galaxy clusters and superclusters on megaparsecs scales) and numerous ill-understood processes, which make the whole field a maze of unsolved, but exciting problems. We present new approximations for numerical treatment of multiphase ISM forming stars. The approximations were tested and calibrated using \textit{N}-body+fluid numerical simulations. We specifically target issues related with effects of unresolved lumpinesses of the gas. We show that the degree of freedom is much smaller than naively expected because of self-regulating nature of the process of global star formation. One of the problems of numerical simulations is related with the uncertainties of approximation of the supernovae (SN) feedback. It is often assumed that the feedback is mainly due to momentum transferred by SN into the ISM. We argue that this may not be true. We present a realistic example of gas actively forming stars with short cooling time for which the SF feedback is important, but the kinetic energy of the gas motion due to SN is negligibly small as compared with the thermal energy of gas.

2 Introduction

Numerical \textit{N}-body+hydro simulations are important tools for making theoretical predictions for galaxy formation in the expanding Universe. Unfortunately, the simulations are mired by two basic problems. i) Results on scales of interest (kpc and larger) crucially depend on much smaller (pc) scales. This is very different from \textit{N}-body problem where the situation on large scales does not depend on what happens on small scales. The reason why small scales are important lies in the nature of the cooling and heating of the gas. Small-scale lumpiness changes the gas cooling rate. The gas heating is defined by how the star formation proceeds on very small scales, not simply by the average star formation rate. ii) There is no theory of star formation (SF). Observations regarding SF are very useful, but they do not cover all important situations.

Nevertheless, the situation is not that grim as it looks. Not all details of the small-scale processes are really important. Recently, Yepes et al.(1997)\cite{1} presented realistic simulations of the galaxy formation in which different parameters (e.g., cooling rates, resolution, SN feedback) were changed dramatically with the goal to find out how the final results are sensitive on the parameters. The final global results (for example, total luminosities and SFR) were remarkably stable when the cooling rates changed by a factor of ten and when the resolution changed by a factor of two. The results for small galaxies were very sensitive to the
feedback parameter, while large galaxies were insensitive even to the SN feedback. Some of the dependencies are easy to understand, but some are more difficult. For example, if the cooling time is very short (as typically is the case), the cooling time is not important. Another reason for stability lies in the nonlinear response of the ISM to the SF. The ISM is typically found in a self-regulating regime when the rate of infall of a fresh gas from outside is defined by the heating of the gas by newly formed gas. If the infall is large, the SF increases (because the gas cools and becomes available for SF), this results in larger heating of the gas by young stars and SN, which stops the infall. This self-regulating evolution of the ISM results in effective “canceling” of the number of free parameters – results are sensitive only to a small number of combinations of the parameters.

The following example illustrates the idea. Let \( x \) and \( y \) be two variables, which describe the situation (e.g., density and temperature of gas). They depend one on the other in a simple, but nonlinear way, which involves four parameters \( a_1, a_2, b_1, b_2 \). The evolution of the system is defined by two differential equations. The system has the same basic structure as a real system: \( \frac{dx}{dt} = a_1 x - b_1 y^2, \frac{dy}{dt} = a_2 y - b_2 x^2 \). The system depends on four parameters \( a_i, b_i \) and on two initial conditions: \( x_0, y_0 \). Thus, six “free parameters” define the evolution of the system in general. With six free parameters one naively would expect that any final configuration is possible. But in the regime of self-regulating evolution, \( \frac{dx}{dt} \approx \frac{dy}{dt} \approx 0 \), and the solution depends only on two parameters \( \alpha = (a_1/b_1)^{1/3} \) and \( \beta = (a_2/b_2)^{1/3} \), and it does not depend on initial values of \( x \) and \( y \).

3 Cooling of gas with multiple phases

The equations describing the evolution of a two-phase medium of hot gas, which emits radiation, and cold clouds (\( T_c = 10^4 K \)), which effectively have stopped cooling, but are capable of producing luminous matter (“stars”), can be written in the form:

\[
\rho_h \frac{dh}{dt} = \frac{\beta}{t_s} [\epsilon_{SN} - A(e_h - e_c)] - \alpha \rho_h^2 \frac{A(T_h)}{\mu^2 m_H^2}, \quad \epsilon_{SN} = 10^{51} \text{erg}/22M_\odot, \quad (1)
\]

\[
\frac{d\rho_h}{dt} = - \frac{C - \alpha \rho_h^2 A(T_h)}{t_s} + \frac{A \beta \rho_c}{t_e}, \quad \beta \approx 0.12, \quad (2)
\]

\[
\frac{d\rho_{gas}}{dt} = - \frac{1 - \beta}{t_s} \rho_c = - \frac{\rho_*}{dt} \rho_{gas} = \rho_h + \rho_c, \quad (3)
\]

where indices \( h, c, \) and \( gas \) refer to the hot, cold, and the total gas components; \( kT = (\gamma - 1)m_H \mu m_\epsilon \). Free parameters \( \alpha \) and \( C \) were calibrated using numerical simulations: \( \alpha = 0.95, C = 2 \). The feedback parameter must be in the range \( A = 50 - 200 \). In order to test our approximations for cooling of multiphase gas we run few numerical simulations of evolution of initially slightly inhomogeneous gas without gravity and without SF. Simulation box is small: 500pc-3kpc. For a real cosmological simulation the whole box would be one resolution element. We use 64\(^3\) PPM code to run the simulations. Initial conditions were either small random gaussian fluctuations with RMS=0.15 or a simple sine-wave perturbation \( \delta \rho \propto \sin(x) \sin(y) \sin(z) \).

Two combinations of the size of the box and the gas density were chosen: i) gas cools very fast (no motion of gas) or ii) the gas cools slowly, and it has time to produce motion of gas across the box. Results are presented in Figure 1.

We also used the initial conditions to make runs with the SF and feedback included. In all cases we observed that after some initial evolution the system settles in a regime of steady “burning” of gas into luminous matter (“stars”). In that regime the energy produced by stars is almost equal to the energy
Figure 1: Cooling of gas in the regime of thermal instability. Full curves are for gas with initial random distribution of density fluctuations with the rms $\sigma = 0.15$. Initially the gas is in the pressure balance and $T = 10^6 K$. The dot-dashed curves are for gas with one sine-wave perturbation of density with the same rms fluctuation as for the full curves. As the gas cools the thermal instability develops. It results in the formation of very dense cold lumps and hotter gas with very low density. The long-dashed curves show evolution of a homogeneous gas with the same initial average density and temperature. The dotted curves show results for our multiphase treatment. It clearly provides much better approximation as compared with the homogeneous gas.
radiated by the gas with the kinetic energy of the gas always being much smaller than the thermal gas energy. In the regime of the self-regulating SF the gas temperature appears to be a constant, which can be found analytically:

\[ \epsilon_h = \left( \frac{C - \alpha}{C(1 - \beta - A\beta)} \right) + \epsilon_c \approx \left( \frac{C - \alpha}{C} \right) \frac{\epsilon_{SN}}{A} \approx \frac{\epsilon_{SN}}{A} \] (4)

Figure 2 presents an example of the evolution of the multiphase gas with the supernovae feedback. The SF was delayed by one cooling time in order to increase the fraction of energy in the form of gas motion. Even in this extreme case, the kinetic energy was much smaller than the thermal energy of the gas. After \( 2 \times 10^7 \) yrs the system was already in the regime of self-regulating SF. The total energy released by forming stars was almost equal to the energy radiated by the gas with the kinetic energy being much smaller than each of the energies. The temperature of the gas was close to the value predicted by equation (4). Note that vastly different initial conditions (one sine-wave or 1/4 million independent fluctuations) resulted in very similar final states of the gas and almost identical rates of conversion of gas to stars.

We thank Volker Muller and the organizing committee of the Potsdam Cosmology Workshop for their hospitality. This work is supported by NSF grant AST-9319970 and NASA grant NAG-5-3842.

References

[1] Yepes, G., Kates, R., Khokhlov, A., Klypin, A., 1997, MN, 284, 235.
Figure 2: Evolution of average gas properties in the case of active star formation and the supernovae feedback. 3D PPM hydro code with 50pc resolution was used. The star formation was allowed only after $10^7$ yrs. The effective time-scale for SF $t_{*eff} = 1.5 \times 10^8$ yrs was much longer than the minimum $t_* = 5 \times 10^7$ yrs imposed by the code.