Placing stars within cosmological simulations

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Abstract. I investigate the process of converting gas into stars within the framework of a standard cosmological model. By examining the set of objects grown in a combined N-body plus smoothed particle hydrodynamics simulation with those obtained in similar models where some of the cold, dense gas was replaced by collisionless “star” particles I show that it is possible to make this substitution without affecting the subsequent gas cooling rate. With even the most basic star forming criteria the masses of isolated objects are nearly identical to the mass of cold, dense gas found within the same objects in a non-star forming run.

No evidence is found to support the contention that converting gas into stars might affect the amount of cold gas obtained in a simulation by retarding the cooling rate within those objects where stars have already formed. In practice, because cold gas can be reheated by shocks but stars remain as such whatever happens the masses of the largest objects found in the star forming runs are generally higher than those in the standard run.

Finally, I demonstrate that an excellent match to the observed star formation rate can be achieved with even a very basic star formation prescription.

Key words: methods; numerical – galaxies; formation; kinematics and dynamics – cosmology; theory – hydrodynamical simulation

1. Introduction

Collisionless cosmological simulations have for several years been expanding our knowledge of how the large scale structure in the Universe formed. The difficulty lies in comparing the dark matter of the models with the observable Universe, where we see starlight from galaxies and X-rays from hot gas. Gas is a dissipational medium; tightly bound structures form which survive the violent evolution of larger objects. When galaxies fall together to form clusters their dark matter halos become stripped and merge together, leaving behind several distinct, bright galaxies within a single dark matter halo. Collisionless simulations lack the dissipational processes that occurred as visible galaxies cooled and formed stars which makes the process of comparing the results to the observations difficult.

Recently several codes have been written that are capable of including a dissipating gaseous component (Katz, Hernquist & Weinberg 1992, Navarro & White 1993, Evrard, Summers & Davis 1994, Tsai, Katz & Bertschinger 1994, Couchman, Thomas & Pearce 1995, Cen & Ostriker 1996, Frenk et al. 1996, Steinmetz 1996).

Most of these groups employ smoothed particle hydrodynamics (SPH) to follow the gas (Monaghan 1992). This allows non-adiabatic heating through shocks and cooling via radiation to be included in the cosmological models and a direct comparison can be attempted between the regions of cold, dense gas and the observed distribution of galaxies.

Here I examine the formation of objects within a cosmological volume. Typically a Milky Way like galaxy will contain 100 or so gas particles with the mass resolution I employ. With this number of particles it is not possible to recover the internal dynamics and structure of the objects but reasonable distribution and multiplicity functions can be obtained.

For a variety of reasons, not least because it saves computational effort, it is useful to convert the gas within cold, dense clumps (or “galaxies”) into “star” particles, which from that point on behave like collisionless dark matter particles. This can be achieved in a variety of ways, with varying degrees of physical motivation. Here I will attempt to show that perhaps the simplest possible choice of assumptions leads to a stable result and so more complicated schemes are perhaps unnecessary. Throughout this paper the term “star” refers to a particle that was once subject to gas forces but has since been converted into a collisionless particle of the same mass. I do not consider any additional
physical processes which might affect a stellar population such as supernova feedback or metal enrichment as these will be discussed in detail elsewhere.

Within this paper I show that one successful way of incorporating star formation within a cosmological simulation without affecting the masses of the final objects is to use a combined density and temperature cut. This alleviates the worry that the action of converting a gaseous particle into a collisionless one might retard subsequent cooling by lowering the local gas density. In practice this is not the case and apart from dynamical considerations we are free to equate the mass of stars found with the mass of cold, dense gas that would have been obtained in a non-star-forming simulation.

I then compare the star formation rate obtained with my preferred method against that observed by Madau (1996). The good agreement between the observations and the simulations demonstrates that reproducing the observed star formation rate is in practice straightforward and is a natural consequence of hierarchical clustering.

2. Simulations

I have run my simulations using a parallel adaptive particle-particle, particle-mesh plus smoothed particle hydrodynamics code (Pearce & Couchman 1997) implemented in CRAFT, a directive based parallel Fortran developed by Cray. It can be run in parallel on a Cray T3D or serially on a single processor workstation and is essentially identical in operation to the publicly released version of Hydra (Couchman, Pearce & Thomas 1996) which is described in detail by Couchman, Thomas & Pearce (1995). This work has been carried out as part of the programme of the Virgo Consortium, a group of astrophysicists interested in large cosmological simulations.

The three simulations presented here were of an $\Omega_0 = 1$, standard cold dark matter Universe with a boxsize of $25h^{-1}$ Mpc. I take $h = 0.5$ throughout this work, equivalent to a Hubble constant of $50\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$. The baryon fraction, $\Omega_b$, was set from nucleosynthesis constraints, $\Omega_b h^2 = 0.015$ (Copi, Schramm & Turner 1995) and I assume a constant gas metallicity of 0.5 times the solar value. Identical initial conditions were used in all cases, allowing a direct comparison to be made between the objects formed. Useful parameters for the runs are listed in table 1.

The initial fluctuation amplitude was set by requiring that the model produced the same number density of rich clusters as observed today. To achieve this I take $\sigma_8 = 0.6$, the present day linear rms fluctuation on a scale of $8h^{-1}$ Mpc (Eke, Cole & Frenk 1996, Viana & Lidelle 1996). Each model began with $64^3$ dark matter particles each of mass $3.1 \times 10^{10} M_\odot$ and $64^3$ gas particles of mass $1.9 \times 10^9 M_\odot$, smaller than the critical mass derived by Steinmetz & White (1996) required to prevent 2-body heating of the gaseous component by the heavier dark matter particles. I employ a comoving Plummer softening of $25h^{-1}$ kpc, which is typical for cosmological simulations but much larger than required to accurately simulate the dynamics of galaxies in dense environments. For a Plummer softening of $25h^{-1}$ kpc the effective softening is around $50h^{-1}$ kpc whilst elliptical galaxies have scalelengths of around $4h^{-1}$ kpc. This dramatic increase in the cross section of the objects will artificially enhance the merger rate and make tidal stripping much more effective.

With only $2 \times 64^3$ particles converting the dense gas into collisionless particles does not result in a large time saving. The total number of steps taken is not reduced by much because the dissipation that occurred as the gas cooled to form dense knots produces tightly bound clumps of stars which require small timesteps if they are not to be disrupted. A modest saving is seen in the CPU time required per step as for stars expensive SPH calculations no longer need to be carried out. The full benefit of converting gas into stars only really becomes apparent within larger $2 \times 128^3$ particle simulations where shorter timesteps are observed (Pearce et al. 1997) if star formation is not employed because the volume contains larger objects which form earlier.

Before star formation can be introduced into a model an adequate treatment of gas cooling is required. In this paper I use the analytic form of Thomas & Couchman (1992). I have implemented the tabulated cooling functions of Sutherland & Dopita (1993) and no significant differences to the results presented here are obtained. In practice the results presented in this paper are not sensitive to the precise form of the cooling function and should hold for all such functions.

The gas ends up in three phases; there is a hot phase, where gas sits in the potential wells formed by the larger objects, and two cold phases, one formed by the collapsed objects and the other formed by gas that has yet to collapse which occupies the void regions. Table 1 lists the percentage of the gas which resides in each of these phases at a redshift of zero. These values are in agreement with those obtained by Evrard, Summers & Davis (1994) at a redshift of 1 (the end of their simulation), where I obtain values of 24 percent hot gas and 72 percent cold gas in voids in all three simulations, the remaining 4 percent is in the form of cold, collapsed gas or stars.

2.1. Star formation details

Stars are formed within the models in two slightly different ways. In both cases once a gas particle has satisfied the relevant criteria its type is simply changed from “gas” to “star” and from then on the particle behaves like a collisionless dark matter particle of the same mass, only experiencing the force of gravity. This “instantaneous” conversion of a gas particle into a star is deliberately crude, reducing the number of free parameters to a minimum and is similar to that employed by Summers (1993). I do
not consider schemes which involve spawning additional particles (e.g. Katz 1992, Navarro & White 1992), redistributing mass or dual identity "schizophrenic" particles (Mihos & Hernquist 1994). All these schemes may increase the tunability of the star forming process but as I will later show they are not required at least in a cosmological situation where the poor mass resolution makes any model of star formation very crude.

In the first model a star is formed if a gas particle has a density exceeding 550 times the mean density in the box and has a temperature below $10^5 K$, converting 11 percent of the gas into stars by the end of the simulation ($Ω_⋆ = 0.11 = 0.006$). This is close to the observed stellar mass fraction, $Ω_⋆ = 0.004$ (Peebles 1993) despite the poor mass resolution of these simulations. This is another demonstration of the well known cooling catastrophe (White & Frenk 1991). The second method is the same as the first except that a gas particle only has a 5% chance of becoming a star on any one step. An overdensity of 550 is quite low compared to the threshold used by other authors (e.g. Navarro & White 1992) but I am forced to adopt this value because of my poor mass resolution and large softening which causes the maximum reliable overdensity obtained within the simulation to be around 2000. In practice cold gas in this regime has little pressure support and so rapidly increases in density.

Within a cosmological simulation it seems non-sensical to adopt a physical density criterion as the basis for a star formation algorithm. The star forming regions are characterised as collapsed clumps of cold, dense particles where the important factor is not the physical density but the overdensity. At a high enough redshift the entire Universe will be at a density above whatever physical threshold is employed, forcing the implementation of an overdensity constraint to prevent star formation at early times. If the star forming region itself could be resolved within a simulation then a physical density threshold might be useful, but when an entire galaxy is only barely resolved such a threshold seems at best problematic.

### 2.2. Identifying groups

Within a simulation volume it is useful to be able to reliably identify a catalogue of all the bound objects. In practice this is a tricky procedure because some degree of merging and disruption of the object set will be taking place at any given time and a binary merger can dramatically affect the position of any given object within the catalogue. The presence of a cooling gaseous component reduces the problem of identifying groups because both density and temperature information is available. The objects being sought are characterised as clumps of cold, dense particles. In principle both density and temperature information could be calculated for the dark matter component but the lack of dissipation and large scatter reduces the usefulness of the local velocity dispersion although others have used the local dark matter density as an aid to defining groups (Gelb & Bertschinger 1994).

To define groups I use the procedure of Thomas & Couchman (1992). By extracting all the gaseous particles which are simultaneously both in a dense region and have a temperature below $10^5 K$ a reduced set of positions is obtained which can then be passed to a friends-of-friends algorithm. When the maximum linking length is small the particles within each clump are linked together. At higher values the recovered object set remains static until neighbouring clumps begin to be linked. This allows us to use a maximum linking length of $60 h^{-1} \text{kpc}$, a value larger than normal because of the highly reduced set of points that are passed to the finder. In practice the maximum linking length can vary over a large range and essentially the same object set be recovered.

Once star formation is implemented the stars themselves provide an additional method for making the initial selection of those particles which might be in groups. For the runs which contain star particles the friends-of-friends finder uses the star positions to produce the group catalogue with the same linking parameters as for the gas runs. With stars the isolated objects are still easy to recognise and define but within dense regions things are much more messy. Clumps of stars are often non-spherical due to tidal distortions and the whole cluster is permeated by a diffuse background light that originates from small systems that have been completely disrupted. The central part of this halo is linked with the mass of the central object but in practice few galaxies are linked together because the stellar systems remain centrally concentrated. In total 86 percent of the stars end up in the object set produced by the group finder. For the gas only run a much higher value of 97 percent is achieved, simply demonstrating the messier nature of runs which include stars. Practically, the merger and halo effects could be alleviated by reducing the value of the linking length used to define the stellar clus-
ters but this would further reduce the percentage of stars lying within resolved objects.

3. Results

3.1. Multiplicity function

The group finder described above produces a catalogue of objects ordered by mass. The effect on the multiplicity function of forming stars using my different prescriptions is shown in figure 1.

The gas particles being considered for conversion into a star should always be both dense and cold, residing within collapsed objects. If only a density threshold were employed it would be necessary to choose a value low enough to allow small, isolated clumps to form stars but also high enough to prevent hot gas particles in the cluster halo: If the resolution were to be increased then these first stars would be seen even earlier. This is the well known “cooling catastrophe” where more and more gas cools as the resolution is progressively increased (White & Frenk 1991). The formation time of the earliest objects also depends upon the size of the volume being simulated: bigger boxes have more room to fit in a high sigma peak of the initial fluctuation spectrum, providing a site where a large cluster will eventually form. If the resolution is fixed bigger boxes will form their first objects earlier.

As can be seen the standard, non-star forming run always has more particles which would have qualified as stars if the same density and temperature cut were employed as for the star forming runs. This is despite the disruption of objects mentioned in the previous section. The reason for this discrepancy is that the star forming algorithm is discrete, but the SPH variables used to measure the state of the gas are averages over some number, $N_{sph}$, of particles (here $N_{sph} = 32$). For a single star to be formed there must be $N_{sph}$ particles close to the star formation threshold and so a zero point offset has to be introduced if the object masses are to be compared. To compensate for this effect I add $\alpha N_{sph}$ onto the mass of all the stellar groups, where $\alpha$ is a parameter between 0 and 1. For simplicity I take $\alpha = 1$ in what follows.

In figure 3 I plot the star formation rate in $M_\odot/yr/Mpc^3$ versus redshift with the observed results from Madau (1996) overlayed. Clearly stars are being over-produced at late times (after a redshift of 1) but this may just be a consequence of the cosmological model employed (standard CDM has lots of evolution at late times). This demonstrates that any star formation formula that is ultimately based upon the gas density and is normalised to produce the correct total mass of stars should be expected to fit the observed star formation rate very well.

As can be seen from figures 1, 2 & 3 the runs with a percentage chance of forming a star on any one step produce almost identical results to their counterparts. The initial motivation for introducing a percentage chance to delay star formation was to assist gas cooling by providing a “seed” of cold gas which was not immediately converted into stars onto which more gas could accumulate. The success of the model with a combined density and temperature cut demonstrates that this concern was unfounded and that delaying star formation via a ran-
Fig. 1. The multiplicity function

Fig. 2. The star forming history
dom chance is an unnecessary complication that in practice simply raises the density threshold at which stars are formed because during the delay introduced the clump collapses further. This has the effect of producing more tightly bound clumps which may then survive subsequent tidal disruption but in practice has little effect upon the simulation. This lack of effect occurs for the same reason that a zero point offset is required; at any one time $N_{sph}$ particles are close to the star formation threshold so the addition of a few extra particles above the threshold has little effect.

3.3. Direct comparison

In figure 4 I show a comparison between the masses of the objects found by the group finder in the standard non-star forming run and the masses of the same objects found in my preferred star forming run, where both density and temperature cuts were employed but without a percentage chance (which has little effect).

The correspondence in mass between the objects in the two runs is very good with only a small scatter. At the high mass end the masses of the objects in the star forming run are in fact higher than the equivalent object in the run without stars. This is because some objects falling into the cluster halos are disrupted and dispersed. When stars are present these subsequently add to the mass of the central object but without stars the gas is reheated and forms part of the hot cluster halo. With a smaller gravitational softening these objects would be more tightly bound and harder to disrupt and so the object masses in the non-star forming run would have been higher.

The few outliers in the upper left quadrant of the figure are due to objects within the star forming simulation that have been linked together by the group finder. This is because with stars the objects often have a small “halo” because they cannot dissipate further once stars have been formed and subsequent mergers and tidal torques lead to messier shapes, forming bridges and spurs which sometimes cause the group finder to link together separate objects. The paucity of objects in this region of the plot clearly demonstrates that overmerging is not a problem with these simulations.

4. Conclusions

The main conclusion of this work is that replacing cold, dense gas with stars within a cosmological simulation can be done with relative ease and to some degree of accuracy without affecting the subsequent cooling rate of the gas. In principle all that is required is that the gas is dense enough but in practice a temperature threshold should also be employed to ensure that hot halo particles are not converted to stars erroneously.

Introducing a percentage chance to delay star formation raises the density threshold and has no affect on the masses of the objects obtained. This and more complicated schemes such as the gradual conversion of a gas particle into a star might be useful if additional physical processes
such as feedback are considered or if a smoother star formation rate is desired but are not required in principle.

It is a fundamental property of the SPH method that if one particle has a certain density and temperature $N_{\text{sph}}$ particles should have similar properties. This leads to a zero point offset in the masses of the stellar objects when compared to the mass of cold, dense gas in a non-star forming run.

Matching the star formation rate obtained within a simulation to that observed is a straightforward exercise with good fits being obtained with even the most basic star formation formulae. This is because the general trend of the observed values, a small rate at early times rising slowly to a peak around a redshift of 1 followed by a decline just mimics the effects of structure formation in any underlying cosmology.

Although the introduction of star formation allows simulations to be carried out more rapidly the simulator should be aware of several additional processes it introduces. Isolated objects are well reproduced whether or not star formation is employed but within dense regions additional dynamical processes are taking place. Obviously the dynamics of a gaseous clump will be different from a collisionless object in an environment where ram pressure stripping and merging are important. Small cold gas clumps can be disrupted as the cluster forms, dissolving into the general cluster halo. The analogous stellar systems will also be tidally disrupted but the stars themselves will survive and contribute to a diffuse cloud of stellar particles that pervades the larger groups. Gas clumps merge quite easily whereas star clumps tend to produce messy associations because once a star has been formed no subsequent dissipation can take place and so reheating events can prove to be a problem.

In summary, converting gas into stars within a cosmological N-body simulation is a viable option and even a basic prescription works well for isolated objects. However, in regions where tidal torques and merging are sig-
significant the differences between collisionless systems and
collisional, dissipating gaseous systems should be carefully
considered and if possible a parallel non-star forming sim-
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