Chapter 6

Conclusions

6.1 Discussion

6.1.1 Computational Cosmology

We have introduced an initial conditions code suitable for the resimulation of individual haloes at extremely high resolution and verified that the basic properties of the haloes – including density profiles and velocity dispersion profiles – remain the same regardless of the mass resolution of the halo. We also introduced a conceptually simple way of marking out the lagrangian regions of haloes and presented details of automated tools for carrying out this process. We also presented some work on code validation on two different codes were compared with one of the standard numerical tests. Both were found to perform adequately.

6.1.2 Statistical Models of the Interstellar Medium

Motivated by the fact that we cannot reasonably resolve the Jeans scale for molecular clouds in galaxy simulations we have introduced a new star formation and feedback prescription. We model the ambient phase of the ISM using a hydrodynamic simulation code and the unresolved molecular gas using a sticky particle prescription. Our model leads to a tightly self-regulating multiphase ISM. The multiphase nature of our star formation prescription avoids a lot of the problems of overcooling that were present in the first generation of star formation models. With the exception of the parameter that controls the molecular cloud coagulation timescale, $v_{\rm stick}$, all the parameters in our model can be tightly constrained by observation, leaving the cloud coagulation timescale as a free parameter that we can adjust to match the observed properties of galaxies. Where possible our model of the ISM has been formulated in such a way that the results of a simulation should be independent of mass resolution. We demonstrated that the large scale properties of our simulations were unchanged over a two orders of magnitude shift in mass resolution.

6.1.3 The Interstellar Medium in Isolated Galaxies

We have applied the sticky particle star formation model to two different types of simulation: the rotating collapse of a gas and dark matter sphere and a model of a quiescent galactic disk. We find that after using the one zone simulation to set the value of the parameters that cannot be determined observationally, the sticky particle model can be applied to the other simulations without any parameter changes.

The simulations of a quiescent disk galaxy reproduce the observed Schmidt law with a slope of 1.4 due to the opposing effects of cloud coagulation and feedback effects. The galaxy also developed a natural three component ISM. Finally we observe supernova heated gas in the galaxy being ejected from the disk either in the form of a galactic fountain, or, when the star formation rate (and associated supernova rate) is sufficient, in the form of strong bipolar outflows. Both of these results arise as a natural consequence of the physics included in our star formation prescription.

Simulations of the collapse of a rotating sphere of dark matter and gas reproduced many of the observed properties of galactic disks, beginning from an initial condition well out of equilibrium. In particular we observe a stellar disk with distinct bulge and disk components, well fitted by the standard exponential and de Vacouleurs density profiles. The fraction of molecular gas in the disk as a function of radius is reproduced, and agrees well with recent observations of nearby galaxies. The observed relation between the disk midplane pressure and the fraction of molecular clouds is also reproduced. We also observe star formation rates comparable to those in disk galaxies and note that our model reproduces the formation of stars in the spiral arms of the galaxy.

6.1.4 Simulating Galaxy-Galaxy Interactions

Using the isolated galaxies that were investigated in the previous chapter we investigate the properties of the ISM during galaxy merger events. We found that the resulting galaxy expressed many of the properties of observed elliptical galaxies, the mass of molecular gas was found to fit will with that in elliptical galaxies of a similar total mass. The stellar density profile matched that found in other simulations, the projected brightness profiles were also well described by the observational fits. The temperature profile of the hot component of the ISM was found to fit well with that observed in nearby galaxies. During the interaction we see that strong tidal arms are generated. It was found that these arms exhibit strong bursts of star formation, as observed in interacting galaxies in the local universe.

The fully self-consistent cosmological simulation produced a disk galaxy that matches many of the observed properties of local galaxies in spite of our crude treatment of metal enrichment by supernovae.

Overall our statistical model for star formation and feedback does a good job of reproducing many of the properties of both quiescent and interacting disk galaxies, and the properties of elliptical galaxies are also closely matched to those in the local universe.

6.2 Future Work

A natural continuation of this work is to extend our investigations to higher redshift through the use of fully cosmological simulations in which we can use our models of the ISM to probe the properties of galaxies of all morphologies over a range of redshifts.

In order to carry this out it is necessary that we incorporate additional levels of complexity into our code. Firstly the addition of stellar population synthesis codes into our outputs will facilitate comparisons between our simulations ond observations. Secondly although in the case of a quiescent disk galaxy it is a fair assumption that the metallicity of the galaxy remains approximately constant over the period we are investigating this is not the case in a fully cosmological simulation. Here the metallicity ranges all the way from 0 at high redshift to $\sim Z_{\odot}$ at redshift zero. The collapse of gas into galaxies will also be very strongly affected by its metallicity (since metallicity can change cooling rates by over an order of magnitude). Incorporation of these two pieces of physics into our simulations will allow us to perform simulations of galaxy formation with an unprecedented level of sophistication.

We can then analyse these galaxies and investigate in detail the buildup and evolution of present day disk galaxies. It will be particularly interesting to observe the effects of the strong galactic winds seen in chapter 4 on the intergalactic medium, both in terms of their effect on QSO spectra and the metal enrichment of the IGM. By combining sophisticated simulation techniques with high resolution resimulation techniques we also hope to be able to resolve the structure and properties of galaxies at all redshifts.

Our second area of active research is in attempting to gain a better understanding of the numerical effects that may affect our results. The two 'traditional' problems with the simulation of cosmological haloes are the 'angular momentum problem' and the 'substructure problem'. Recent results (see e.g. Governato et al. (2006)) suggest that increasing the mass resolution of a simulated halo alleviates the angular momentum problem, and galaxies with enough particles ($\sim$ millions within the virial radius) begin to form extended stellar disks. It is additionally unclear in many circumstances how a particular author's star formation and feedback prescriptions are affected by the mass resolution of the simulation and how this may affect the properties both of the central galaxy in a halo and its subhaloes.

We plan to carry out a comprehensive study into the effects of mass resolution on the properties of simulated galaxies using the initial conditions code and simulations introduced in chapter 2 in order to gain an understanding of how particle number affects the star formation and feedback in the subhaloes of typical MW sized haloes and how resolution effects control the early history and buildup of a simulated galaxy.