

CDM, Feedback and the Hubble Sequence

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Abstract. We have performed TreeSPH simulations of galaxy formation in a standard Λ CDM cosmology, including effects of star formation, energetic stellar feedback processes and a meta-galactic UV field, and obtain a mix of disk, lenticular and elliptical galaxies. The disk galaxies are deficient in angular momentum by only about a factor of two compared to observed disk galaxies. The stellar disks have approximately exponential surface density profiles, and those of the bulges range from exponential to $r^{1/4}$, as observed. The bulge-to-disk ratios of the disk galaxies are consistent with observations and likewise are their integrated $B - V$ colours, which have been calculated using stellar population synthesis techniques. Furthermore, we can match the observed I -band Tully-Fisher (TF) relation, provided that the mass-to-light ratio of disk galaxies is $(M/L_I) \sim 0.8$. The ellipticals and lenticulars have approximately $r^{1/4}$ stellar surface density profiles, are dominated by non-disklike kinematics and flattened due to non-isotropic stellar velocity distributions, again consistent with observations.

Keywords: Cosmology, galaxy formation, numerical methods

1. Introduction

The hierarchical Cold Dark Matter (CDM) structure formation scenario has proven remarkably successful on large (cosmological) scales. On galactic scales it has encountered a number of problems, most notably the angular momentum problem, the over-cooling problem, the missing satellites problem and the central cusps problem. Inclusion of the effects of energetic stellar feedback processes in galaxy formation simulations may help to cure a number of these problems as indicated by, e.g., the “toy” models of Sommer-Larsen et al. (1999, SLGV). Recently Sommer-Larsen & Dolgov (2001, SLD) showed that by going from the CDM structure formation scenario to warm dark matter (WDM) scenarios one can alleviate and possibly even completely overcome the angular momentum problem, and complementary work of Colin et al. (2000) shows this to be the case also for other of the above problems. Fine-tuning of the warm dark matter particle mass to about 1 keV is required, however. In contrast the salient feature about “conventional” CDM is that as long as the dark matter particles are much heavier than one keV, the actual particle mass does not matter for structure formation.

We have recently completed a series of considerably more elaborate CDM galaxy formation simulations with very encouraging results: We find that a mix of disk, lenticular and elliptical galaxies can be obtained in fully cosmological (Λ CDM), gravity/hydro simulations invoking star-formation, energetic stellar feedback processes and a meta-galactic UV



field. These results, together with results on disk gas infall histories and stellar age distributions, hot halo gas properties, global star formation histories etc. are presented in detail in Sommer-Larsen et al. (2002).

2. The simulations

Star-formation efficiencies are assumed to be related to the thermal history of the gas effectively making the efficiencies large (~ 1) at early times ($z > 4\text{--}5$) and much smaller (~ 0.01) at later times. Early star-formation is assumed to be either a) self-propagating or b) only “local”, the former resulting in the strongest bursts and feedback events. The early, fast star formation is assumed to be triggered when the gas density of an SPH particle exceeds a certain critical value, chosen to be $n_{\text{H},\text{fast}} = 0.3 \text{ cm}^{-3}$. The conversion of such an SPH particle into a star particle may or may not trigger a burst of self-propagating star formation (SPSF) in the cold, dense gas surrounding it: in scenario a) not only the SPH particle which gets above the critical density threshold, but also its neighbouring cold and dense SPH particles with densities above $n_{\text{H},\text{fast,low}} (< n_{\text{H},\text{fast}})$ are triggered for conversion into star particles on their individual, dynamical timescales. Such SPSF is observed in some star-burst galaxies (e.g., in expanding super-shells — see Mori et al. 1997). In scenario b) only the initial SPH particle above the critical density threshold is triggered for star formation on the dynamical time scale.

We selected 12 dark matter halos from a cosmological Λ CDM N-body simulation for the galaxy formation simulations. The masses of these halos spanned more than a factor of 10 and their characteristic velocities V_{200} range from 100 to 250 km/s. After resampling the galaxy formation simulations consisted of 30000-150000 SPH+DM particles. We started out by running all 12 galaxy simulations using the SPSF prescription with a lower density threshold of $n_{\text{H},\text{fast,low}} = 0.1 \text{ cm}^{-3}$. Seven of the resulting galaxies at $z=0$ had distinctly disk galaxy like morphologies and kinematics, the remaining 5 lenticular (S0) or elliptical like morphologies and kinematics. 4 additional series of simulations were subsequently run for the 7 disk galaxies: Three using again early SPSF with $n_{\text{H},\text{fast,lower}} = 0.05, 0.2$ and 0.25 cm^{-3} and one series with fast, early, but non-SPSF. The four choices of $n_{\text{H},\text{fast,lower}}$ results in conversion of 2–5% of the gas in the simulations into stars in the early bursts. In the models without SPSF about 1% of the gas is turned into stars in the early bursts.

3. Results

The disk galaxies have the bulk of their stars on approximately circular orbits in a disk, most of the rest of the stars in an inner, bulge-like component and finally a small fraction in a round and dynamically insignificant stellar halo surrounding the galaxies. The disk galaxies

formed in our simulations are hence qualitatively quite similar to the Milky Way and other disk galaxies. Of the remaining 5 galaxies, two have a minor fraction of the stars on nearly circular, disk orbits; we classify these as lenticulars (S0s), and the remaining three have no stars at all on disk like orbits; we classify these as ellipticals.

The disk galaxies have approximately exponential stellar disk surface density profiles and exponential to $r^{1/4}$ bulge profiles, all in good agreement with observations. The lenticular and elliptical galaxies are characterized by approximately $r^{1/4}$ stellar profiles.

The bulges of the disk galaxies are generally confined to being within $r_B \sim 1 - 1.5$ kpc from the centers of the galaxies. Bulge-to-disk ratios were determined by extrapolating the nearly exponential disk profiles outside of r_B to the center of the galaxies. Using these decompositions (which make no assumptions about the bulge surface density profiles) the specific angular momenta of the stellar *disks* were estimated taking explicitly into account also the region with overlap between disk and bulge. Characteristic circular speeds V_c for the disk galaxies were calculated using the approach of SLD, but as an addition taking into account also the dynamical effect of the bulges.

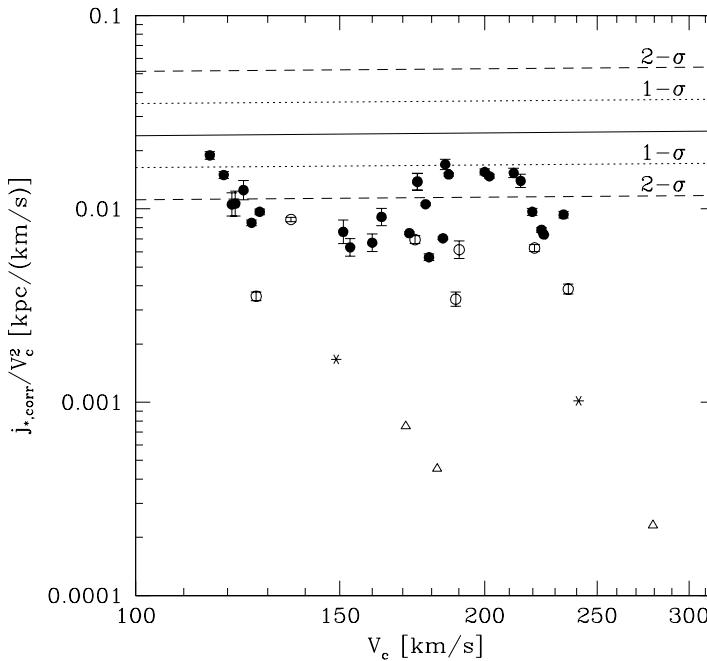


Figure 1. Normalized specific angular momenta for all galaxies. Filled circles: disk galaxies formed in simulations with SPSF, open circles: disks formed in simulations without SPSF, star symbols: S0's and triangles: E's.

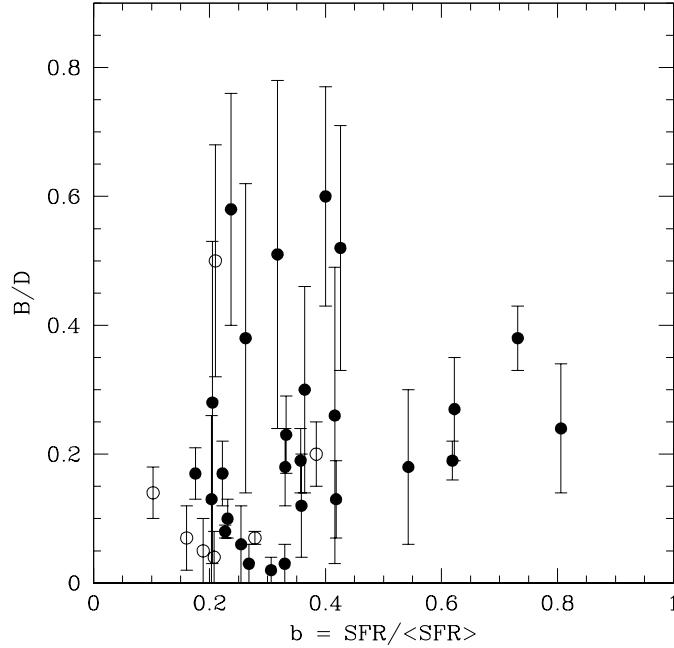


Figure 2. Stellar bulge-to-disk ratios for the 35 disk galaxies — symbols as in Fig. 1.

In Figure 1 we show the “normalized” specific angular momenta $\tilde{j}_* = j_*/V_c^2$ of the final disks formed in all 35 disk galaxy simulations as a function of V_c . As argued by SLGV one expects \tilde{j}_{disk} to be almost independent of V_c on both theoretical and observational grounds. Also shown in the figure is the median “observed” value of \tilde{j}_{disk} , calculated as in SLGV and SLD for a Hubble parameter $h=0.65$, together with the observational 1- σ and 2- σ limits. As can be seen from the figure, the specific angular momenta of the stellar disks from the SPSF simulations lie only about a factor of two below the observed median (the specific angular momenta of the disks from the SPSF simulations have been spin-parameter corrected — see SLD). This is about an order of magnitude better than what is obtained in similar CDM simulations without energetically effective, stellar feedback processes, as discussed by many authors, and almost as good as was obtained by SLD for WDM. The simulations without SPSF and the associated, strong feedback events do not do as well. Also shown in the figure are the normalized specific angular momenta of the two lenticular and three elliptical galaxies. These are about an order of magnitude smaller than those of the disk galaxies, broadly consistent with observations.

Figure 2 shows the bulge-to-disk ratios B/D of the 35 disk galaxies versus the birthrate parameter b , which is the ratio of the current to the average past star formation rate. b is a disk galaxy type indicator, with $b \sim 0.1$ for Sa's increasing to $b \sim 1$ for Sc's (Kennicutt, Tamblyn & Congdon 1994) The trend (or rather, lack of trend) seen in Figure 2 is broadly consistent with observationally determined (and 2-D decomposed) I and K -band B/D s, which trace the *mass* bulge-to-disk ratios fairly well - see Sommer-Larsen et al. (2002).

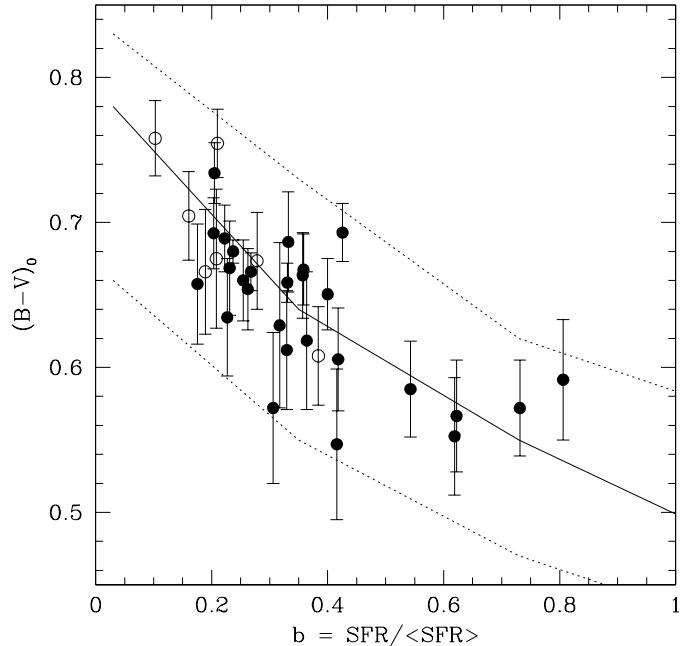


Figure 3. Integrated $B - V$ colours for the 35 disk galaxies, calculated using stellar population synthesis techniques — symbols as in Fig. 1. Also shown (solid line) are the mean observational values for disk galaxies from Roberts & Haynes (1994) and the observational $1-\sigma$ limits (dotted line).

Integrated $B - V$ colours were obtained for the galaxies by stellar population synthesis techniques. In Fig. 3 we show these for the 35 disk galaxies vs. the b parameter. Also shown are observations — the general agreement is excellent. Finally, in Fig. 4 we show $M_*(V_c)$ of the final disk galaxies formed in 35 runs together with the I -band Tully-Fisher relation (TF) for $h=0.65$, converted to mass assuming mass-to-light ratios (M/L_I) = 0.5, 1.0 and 2.0. The slope of the “theoretical” TF matches that of the observed very well for a constant mass-to-light ratio, which is required to be $(M/L_I) \sim 0.8$, similar to the findings of SLD for their WDM simulations. Such a low value is consistent with recent, dynamically estimated mass-to-light ratios for disk galaxies, the

mass-to-light ratio of the Milky Way (Fig. 4) and can be obtained from stellar population synthesis models provided an IMF somewhat less “bottom-heavy” than the Salpeter law is used (Portinari, Sommer-Larsen & Tantalo 2002, Sommer-Larsen et al. 2002).

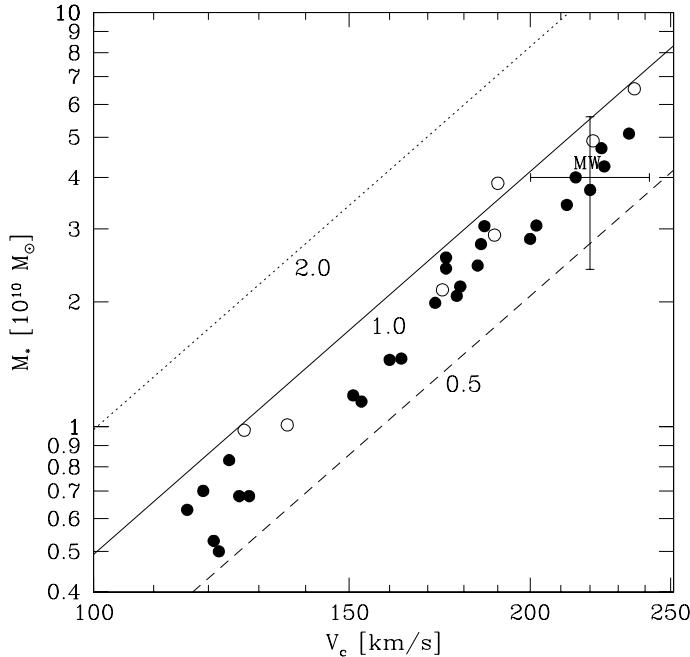


Figure 4. The stellar mass “Tully-Fisher” relation for the 35 disk galaxies — symbols as in Fig.1. Error bars marked MW: The stellar mass of the Milky Way. Lines: observed TF relation for $(M/L_I) = 0.5, 1.0$ and 2.0 - see Sommer-Larsen et al. (2002) for details.

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