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Cosmological formation of disc galaxies

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Abstract. We review the current status of cosmological simulations of the formation and evolution of disc galaxies, discussing in particular the Tully-Fisher relation and its redshift evolution.

In the current picture of cosmological disc formation, due to Fall & Efstathiou (1980), discs form by dissipative collapse of hot halo gas in dark matter (DM) haloes. The resulting centrifugally supported disc has a realistic size provided the infalling gas retains the initial angular momentum (AM). This paradigm inspired semi-analytic models linking the properties of discs to those of the host DM haloes in the Cold Dark Matter (CDM) scenario (see e.g. Dutton *et al.* 2006 and Gnedin *et al.* 2006 for two recent versions).

In cosmological simulations including baryonic physics, however, galactic disc sizes turn out to be too small, by a factor of 10–20 (Navarro *et al.* 1995) because the hierarchical bottom-up assembly combined with gas (over)cooling at early times, forms small dense gas clouds which are then subject to dynamical friction in the DM halo, losing energy and AM — mostly by torques in the last major merger (D'Onghia *et al.* 2006).

Warm Dark Matter cosmology, which suppresses small scale structure reducing overcooling and related problems, has been suggested as a solution for the AM problem (Sommer-Larsen & Dolgov 2001). Within the more standard CDM cosmology, efficient stellar feedback at early epochs has proven an effective way to disrupt and disperse the early dense clouds, decoupling gas from small DM structures (Thacker & Couchman 2001; Sommer-Larsen *et al.* 2003; Governato *et al.* 2006). We have just learned (G. Hensler, this symposium) that in dedicated simulations of supernova feedback it is quite difficult to deposit blast energy efficiently into the surrounding interstellar medium. Cosmological simulations however indicate that, to form realistic disc galaxies, feedback needs to be efficient at least at early epochs, by whatever means (e.g. different gas conditions or different stellar Initial Mass Function at early epochs, hypernovae, AGN feedback...); while at low redshifts, strong feedback may even be counterproductive to the formation of discs out of steady cool–out of halo gas. Implementing this effect in CDM simulations, one can obtain realistic discs, although the bulge–to–disc ratios tend to be quite large and the overall scalelength/AM of the galaxy is still about a factor of 2 lower than observed, especially for Milky-Way sized or larger galaxies (Portinari & Sommer-Larsen 2006).

The standard picture of disc formation (including the solution of the G dwarf problem and of Robert's paradox) implies steady infall of halo gas; but the X-ray emission of the corresponding cooling flows was not observed at the levels predicted by semi–analytical models. Alternative scenarios were thus invoked, for instance cold accretion (Birnboim & Dekel 2003) which however is likely to apply just to sub–L_* galaxies (e.g. polar ring galaxies; B. Moore, this symposium). Here, cosmological simulations have registered an important success by demonstrating that the level of X-ray emission to be expected is more than one order of magnitude lower than predicted by simple cooling flow models, and that it is a steep function of disc mass, $L_X \propto V_c^7$ (Toft *et al.* 2002); correspondingly, the baryonic fraction in the hot halo gas is an increasing fraction of V_c and is comparable to the disc mass for Milky Way–sized galaxies (Sommer–Larsen 2006). At the sensitivity of current experiments, X-ray emission from galactic cooling flows can be detected only for massive discs with $V_c \sim 300$ km/sec and it was indeed finally observed with Chandra, at the predicted levels of surface brightness and temperature, in NGC 5746, a massive, quiescent edge–on spiral (Pedersen *et al.* 2005; Rasmussen *et al.* 2006). Together with extraplanar HI emission (F. Fraternali and B. Moore, this symposium) this is the first direct evidence of the long sought–for infall of halo gas forming galactic discs.

As to the Tully-Fisher (TF) relation, the locus of simulated galaxies is offset by about 1 σ, to high V_c's and/or low luminosities, with respect to the empirical TF locus (Portinari & Sommer-Larsen 2006). Among the reasons that may contribute to the offset:

- adiabatic contraction, removing which is however not enough to cancel the offset, so that a sort of "adiabatic expansion" may be necessary (Dutton *et al.* 2006);
- with respect to the "concordance" LCDM model ($\Omega_M = 0.3$, $\Lambda = 0.7$, $\sigma_8 = 0.9$) the recently revised set of cosmological parameters indicated by WMAP3 ($\Omega_M = 0.26$, $\Lambda = 0.74$, $\sigma_8 = 0.75$; Spergel *et al.* 2006) correspond to lower concentrations for DM haloes, affecting the zero-point of the TF relation (Navarro & Steinmetz 2000);
- a more "bottom-light" IMF than the standard Solar Neighbourhood one, would yield lower mass–to–light ratios, brightening the zero-point of the TF relation; this hypothesis is appealing since the Milky Way itself is offset from the TF relation by about as much as simulations adopting Solar Neighbourhood-like IMFs (Flynn *et al.* 2006).

The predicted evolution of the stellar mass TF relation is negligible, just 20–30% (at fixed V_c) from z = 1 to 0, in agreement with Conselice at al. (2005) and Flores *et al.* (2006). The individual galaxies actually grow significantly in stellar mass in the same redshift range, up to a factor 1.5–2; however, an increase in disc mass induces a corresponding increase in V_c so that the growth of the galaxy largely occurs along the TF relation, with minimal effects on the TF zero point (Navarro & Steinmetz 2000). Due to the aging of the stellar populations (only partly compensated by ongoing star formation in discs), a negligible evolution of the stellar mass TF relation is inevitably accompanied by a significant dimming in the luminosity, by 0.7 (0.85) mag up to z = 0.7 (z = 1) in B–band, with a negligible predicted evolution in the slope.

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