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Simulations of Large Scale Structure Formation: The Connection to Smaller Scales

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Abstract. Maps of the cosmos, in particular maps of the cosmic microwave background and of the large scale distribution of galaxies have been crucial ingredients in the development of the standard model of structure formation, sometimes also labeled "concordance model". This model has proven to be remarkably successful in explaining an impressive array of observations on scales of hundreds of kpc to thousands of Mpc. In this contribution I will attempt to extend those studies to smaller, (sub)galactic scales and will confront detailed gas-dynamical simulations of the formation of individual galaxies with observational data on these scales, reporting some successes and failures of this endeavor. Ongoing surveys that are mapping the distribution of stars in the Milky Way should be able to clearly identify the imprints of the hierarchical galaxy formation process providing an independent check of the validity of the structure formation paradigm.

1. Introduction

Hierarchical clustering is at present the most successful model for structure formation in the universe. Actually, its success is so pronounced that the last few years have seen a disturbing lack of any alternative structure formation model that at least to some extent can rival hierarchical clustering in its success and its predictive power.

Among the hierarchical models, the so-called (concordance) ΛCDM model is consistent with an impressive array of well-established fundamental observations including the age of the universe as measured from the oldest stars, the extragalactic distance scale as measured by distant Cepheids, the primordial abundance of the light elements, the baryonic mass fraction of galaxy clusters, the amplitude of the Cosmic Microwave Background fluctuations, the present-day number density of massive galaxy clusters, the shape and amplitude of galaxy clustering patterns, the magnitude of large-scale coherent motions of galaxy systems, and the world geometry inferred from observations of distant type Ia supernovae, among others.

However, most of these tests are restricted to length scales in excess of 1 Mpc and mass scales above that of typical galaxies like the Milky Way. These also correspond to length scales that have been used to calibrate the free parameters of the model. In this contribution I will address how structures on smaller, maybe even subgalactic scales, i. e. scales far remote from those used to calibrate the model, can be used to provide an independent check of the validity of the ΛCDM paradigm.

2. Gas-dynamical Simulations of Galaxy Formation

The work reported in this contribution is based on the outcome of a suite of gas-dynamical simulations of the formation of individual galaxies in the "concordance" CDM model with a non-zero cosmological constant (ΛCDM: $\Omega = 0.3$, $h = 0.65$, $\Omega_b = 0.04$, and $\Omega_\Lambda = 0.7$). These simulations have been performed using GRAPESPH, a code that combines the Smoothed Particle Hydrodynamics (SPH) approach to numerical hydrodynamics with a direct summation N-body integrator optimized for the special-purpose hardware GRAPE (Steinmetz 1996). GRAPESPH is fully Lagrangian and highly adaptive in space and time through the use of individual particle smoothing lengths and time steps. It is thus optimally suited to study the formation of highly non-linear systems such as individual galaxy systems in a cosmological context. The following physical processes have been incorporated: the self-gravity of gas, stars, and dark matter, a full $3D$ hydrodynamical treatment of the gas, and radiative and Compton cooling. A simple recipe accounts for transforming gas into stars and for incorporating the feedback of mass and energy into the gaseous component driven by evolving stars.

Star formation is modeled by creating new collisionless "star" particles in Jeans-unstable, collapsing regions at a rate given by $\dot{\varrho}_\star = c_\star \varrho_{\rm gas} / \max(\tau_{\rm cool}, \tau_{\rm dyn})$. Here $\varrho_{\rm gas}$ is the local gas density, $\tau_{\rm cool}$ and $\tau_{\rm dyn}$ are the local cooling and dynamical timescales, respectively, and $c_\star$ is a star formation "efficiency" parameter. After formation, "star" particles are only affected by gravitational forces, but they devolve energy to their surroundings in a crude attempt to mimic the energetic feedback from supernovae: 10^{49} erg (per $M_\odot$ of stars formed) are injected into the surrounding gas about 10^7 yr after their formation. This energy is invested mostly in raising the internal energy (temperature) of the gas, but a fraction f_v is invested in modifying the bulk motion of the gas surrounding star forming regions.

The star formation prescription invokes two free parameters, the star formation efficiency $c_\star$ and the fraction f_v of the supernova energy that is invested in modifying the bulk motion of the gas surrounding star forming regions. The star formation parameters are calibrated such that Kennicutt's (1998) relation between the HI surface density and the star formation rate per unit area (Schmidt's law) is reproduced in isolated galaxy test cases.

Figure 1 depicts the outcome of one of the most recent simulations, an early-type disk galaxy that formed in a halo that experiences a number of major merger events in its early formation history ($z > 1$) but no major merger below a redshift of 1. This object is represented by $\approx 36\,000$ gas particles and more than $100\,000$ star particles. This resolution is sufficient to allow a detailed study of its photometric and dynamical properties, including the identification of different stellar populations by age or by kinematics.

3. The Origin of Disk Galaxy Scaling Laws

The success of such a model can be further assessed by testing to what extent such a model can reproduce scaling relations that link total luminosity, rotation speed, and angular momentum of disk galaxies such as the Tully–Fisher (TF)

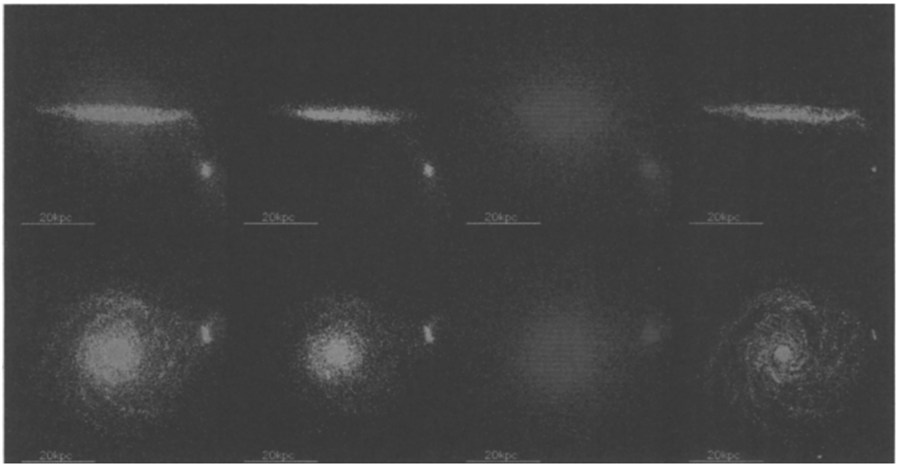

Figure 1. Two orthogonal projections of the baryonic component of a $z = 0$ spiral galaxy. The top row displays an edge-on view, the bottom row a face-on view. The leftmost picture shows a composite of all stars and gas, followed by (from left to right) separate pictures for young stars ($t < 2\,\mathrm{Gyr}$), old stars ($t > 8\,\mathrm{Gyr}$), and for gas alone.

relation. Figure 2 (left) shows the results of such an investigation, the simulated I-band TF relation at $z = 0$ for the ΛCDM and the ΛWDM scenario. The simulated TF relation is compared with the data of Giovanelli et al. (1997), Mathewson, Ford, & Buchhorn (1992) and Han & Mould (1992). The slope and scatter of the simulated TF relation are in fairly good agreement with the observational data. This result also holds in other band passes: the model TF relation becomes shallower (and the scatter increases) towards the blue, just as in observational samples (see Steinmetz & Navarro 1999).

The model TF relations are very tight. In the I-band the *rms* scatter is only 0.25 mag, even smaller than the observed scatter of $\sim 0.4\,\mathrm{mag}$. This must be so if the results are to agree with observations: scatter in the models reflects the intrinsic dispersion in the TF relation, whereas the observed scatter includes contributions from both observational errors and intrinsic dispersion. If, as it is usually argued, both effects contribute about equally to the observed dispersion in the TF relation, then the intrinsic scatter in the I-band should be comparable to the $\sim 0.25\,\mathrm{mag}$ found in the models.

In addition, the zero-point is in rough agreement with observational data; at closer inspection the simulated galaxies appear to be $\sim 0.3\,\mathrm{mag}$ too dim. This disagreement may be attributed to a still sub-optimal modeling of the star formation history in these models. Due to the particular parameterization of star formation, a large fraction of stars form already at high redshift resulting in a fairly high stellar mass-to-light ratio of 2-2.5 in I-band while observations indicate a value closer to 1-1.5 (Bottema 1997). It is also interesting that the zero-point of the TF relation seems to strongly depend on the assumed cosmological scenario. A similar simulation performed for a $\Omega = 1$, $\Lambda = 0$ CDM (not shown in Figure 1) scenario results in a very serious disagreement of the

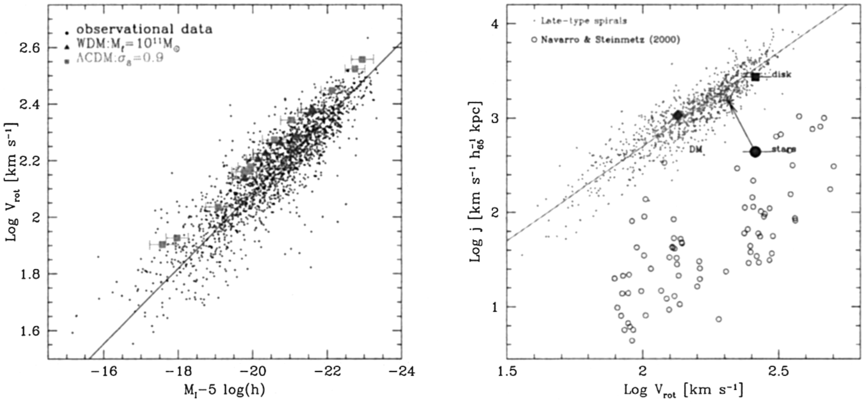

Figure 2. Left: I-band Tully-Fisher relation from the sample of Mathewson et al. (1992), Han & Mould (1992) and Giovanelli et al. (1997). The simulated galaxies are shown by filled squares and triangles. Error bars denote uncertainties owing to the adopted IMF. Slope and scatter of the TF relation are well reproduced, but compared to late-type disks they appear about 0.3 mag too faint, indicative of a too high mass-to-light-ratio in the simulations. Right: Velocity-size relation. Small filled circles correspond to late-type spirals mostly taken from the samples of Mathewson et al. (1992) and Courteau (1997). Open circles correspond to the simulations by Navarro & Steinmetz (2000b), which are similar to the ones presented here, but of lower resolution. The location of the dark matter halo in this plane is shown by the filled diamond, assuming $V_{\rm rot} = 134$ km s^{-1}. The filled circle corresponds to the simulated galaxy, assuming that the rotation speed is that measured at $R = 2.2\,R_{\rm d} = 11$ kpc. The solid square indicates the location of the disk component, computed adopting the same specific angular momentum estimator as applied to observed data, $j = 2\,R_{\rm d}\,V_{\rm rot}$. The agreement indicates that the size of the disk component is similar to that of late-type spirals of similar $V_{\rm rot}$. The arrow points to where the simulated galaxy would be if the spheroidal component were removed. The disk component of the simulated galaxy is structurally similar to observed late-type spirals.

zero point with the data, the simulated $\Omega = 1$ TF relation being almost two magnitudes too faint at a given rotation speed (Navarro & Steinmetz 2000a,b)

Another interesting clue on the origin of the Tully-Fisher relation is that the small scatter and the zero-point (for a given cosmological scenario) is only weakly dependent on the particular star formation and feedback parameterization: very similar results can be obtained for quite different star formation prescriptions (Steinmetz & Navarro, 1999). This is a surprising result since the fraction of baryons that ends up in a disk strongly depends on the particular feedback model and can vary by factors of 3–5 between different parameterizations.

The weak dependence of the scatter on the feedback parameterization is an immediate consequence of how the rotation velocity of the galactic disk responds to changes in the ratio between stellar and dark mass. As more and more baryons assemble in the central stellar disk, their luminosity increases but so does the disk rotation velocity due to the gravity of the additional matter near the center.

This effect is amplified as the additional gravity pulls dark matter towards the center. Consequently a variation in the star to dark matter fraction results in a shift predominately parallel to the TF relation which thus does not cause substantial additional scatter (see Navarro & Steinmetz 2000a,b for a detailed discussion).

A related, but more serious problem can be identified in the velocity-size relation: model disk galaxies appear far too concentrated (Navarro & Benz 1991, Navarro, Frenk, & White 1995, Navarro & Steinmetz 1997). This problem is particularly apparent in simulations of lower numerical resolution that are unable to resolve individual galactic components. Figure 2 (right) demonstrates clearly that the spins of gaseous simulated disks are about an order of magnitude lower than that of observed galaxies. This is a direct consequence of the formation process of the disks. Most of the disk mass is assembled through mergers between systems whose own gas component had previously collapsed to form centrally concentrated disks. During these mergers, and because of the spatial segregation between gas and dark matter, the gas component transfers most of its orbital angular momentum to the surrounding halos. While the specific angular momentum of dark matter halos increases with decreasing redshift, that of gaseous disks decreases (Navarro & Steinmetz 1997).

The most recent suite of high resolution gas dynamical simulations (Steinmetz & Navarro 2002) sheds additional light on the origin of this "angular momentum catastrophe" and how it may be solved. The filled solid circle labeled "stars" in Figure 2 (right) represents the location of the stellar component of the simulated disk galaxies depicted in Figure 1. The horizontal "error bar" in this symbol indicates the uncertainty in the rotation speed of the disk resulting from the declining shape of the rotation curve owing to its large bulge component, which prevents us from assigning an unambiguous characteristic rotation speed to the simulated galaxy. We follow standard practice (see, e.g., Courteau 1997) and choose $V_{\rm rot} = 260$ km s^{-1}, the velocity at $R = 2.2\,R_d = 11$ kpc, to characterize the simulated galaxy. The "error bar" spans the range of velocities in the disk between $R = 5$ and 21 kpc. Correcting for the dominant influence of the bulge component may thus lead to a disk component that is structurally very similar to observed late-type spirals.

One important qualification to the angular momentum problem is that specific angular momenta j are quite difficult to measure observationally, and that the observational data shown in Figure 2 assume that the luminous material is distributed in an exponential disk of scale length R_d with a flat rotation curve, for which $j = 2\,R_d\,V_{\rm rot}$. Computing the angular momentum in the same manner leads to a much higher estimate of the angular momentum of the simulated galaxy; for $R_d \approx 5$ kpc and $V_{\rm rot} = 260$ km s^{-1} we find $j \approx 2.6 \times 10^3$ km s^{-1} kpc (for $h = 0.65$, see solid square labeled "disk" in Figure 2). In other words, the *size* of the disk component, estimated from the disk/spheroid photometric decomposition is similar to that of late type spirals of comparable rotation speed. Were the angular momentum of the simulated galaxy not weighed down by the massive, slowly-rotating spheroidal component, it would match well that of observed spirals. This provides further evidence that the difficulty in reconciling the properties of the simulated galaxy with that of observed spirals lies in the presence of the dense, slowly-rotating spheroid that dominates the luminous stellar component.

The solution to the angular momentum problem thus may lie in a feedback model that considerably reduces star formation in the very first proto galactic clumps and/or that keeps the baryons outside of the first collapsing structures. This will suppress the formation of a massive bulge component and ensure a diffuse infall of gas reducing the angular momentum transport due to dynamical friction. The delay in star formation may also reduce the mass-to-light ratio of the model galaxies resulting in a better match to the zero point of the Tully-Fisher relation.

4. Remnants of the Hierarchical Formation Process in the Milky Way

The key feature of any hierarchical clustering model is that structure forms in a series of mergers between objects of progressively larger mass. Over the past decade, ample evidence has been found in the Galaxy and in M31 that such mergers have played an important role in the formation of their stellar halos (Ibata, Gilmore, & Irwin 1994; Helmi et al. 1999; Majewski et al. 2003). The role such events have played in building up the galactic disk component is much less clear.

While it is widely believed that mergers cannot have contributed considerably to forming the disk of the Milky Way owing to its small scale height, the gas dynamical simulations reported above (Abadi et al. 2003a,b) suggest that mergers play a prominent role in shaping the galactic disk. Photometrically, the model galaxy shown in Figure 1 resembles a typical early-type spiral galaxy: a disk that is composed of young stars and gas surrounds a more centrally concentrated spheroid of older stars. Kinematically the object consists of at least two stellar components: a hot spheroid with an equal number of stars on co- and counter-rotating orbits with a large range of eccentricities, and a cold thin disk of stars on nearly co-rotating circular orbits. Besides these two distinct components, a third component of stars with the same sense of rotation as the thin disk but that, however, relies less on rotation for its support, reminiscent of a thick disk component. A further, more detailed analysis reveals interesting features with immediate implications for the formation history of disk galaxies like our Milky Way (Abadi et al. 2003a,b):

- The main origin of the thick disk is *not* a thin disk that has been heated by collision events. The thick disk consists to at least 60% of tidal debris from satellite accretion events. These satellites preferentially came in on orbits co-planar with the disk and were roughly circularized by the process of dynamical friction. The fraction of thick disk stars with such an origin increases with the age of the stars and exceeds 90% for stars older than 10 Gyr.

- About 15% of the stars that by their kinematics (nearly circular orbits) can be classified as thin disk stars were formed *before* the last major merging event. Like the thick disk component, these stars have not been formed out of a gaseous disk, but have been accreted from disrupted satellites whose orbital plane coincides with the plane of the disk.

- Considering the stellar spheroid, only ≈ 50% of stars stem from disrupted satellites (preferably on orbits that are strongly tilted with respect to the orientation of the disk), while the remaining 50% may be traced to a major merging event at $z \approx 1.5$ that dispersed the luminous, disk-like progenitor.

These interesting features have gained support by some recent observations. Helmi et al. (2003) demonstrated that the recently discovered coherent structure at large Galacto-centric distance and low Galactic latitude spanning about 100 degrees on the sky (Yanny et al. 2003; Ibata et al. 2003) can well be interpreted as tidal debris of a disrupted satellite located in the outer disk of the Galaxy, predicting corresponding substructure in the orbital distribution of the stars in the disk. The recent report of a galaxy being cannibalized in the Milky Way disk (Martin et al. 2004) provides additional support to such a scenario. Navarro, Helmi, & Freeman (2004) argued that even some of the Eggen moving groups, in particular the Arcturus group, may be remnants of satellite accretion onto the disk of the Galaxy pretty much in a fashion as described above.

5. RAVE: the RAdial Velocity Experiment

The previous paragraph indicates that many of the clues to the fundamental problem of galaxy formation in the early Universe lie locked up in the motions and chemical composition of stars in our Milky Way galaxy. Consequently, significant effort has been placed into planning the next generation of large-scale astrometric surveys like GAIA, which aims at mapping out the phase space of the Galaxy by the middle of the next decade using about a billion stars. On a shorter timescale, many issues will be addressed by ground-based surveys like RAVE[1].

The RAdial Velocity Experiment RAVE is an ambitious program to conduct a survey to measure the radial velocities, metallicities and abundance ratios for at least a million stars using the 1.2-m UK Schmidt Telescope of the Anglo-Australian Observatory (AAO) over the period 2006 - 2010. A pilot program of 10^5 stars has been started in April of 2003 and is carried out using the existing 6dF facility in unscheduled bright time (7 days per month) over the period 2003–2005. After one year of operation, about 32000 spectra with a resolution of R=7000 have been collected with a resulting accuracy of about 2 km/sec.

In its most simple incarnation, it is planned to extend the survey after June of 2005 at 25 nights per month. This will yield a collection of spectra of about a million stars by the end of 2010. In a more ambitious version and including a northern counterpart, a collection of up to 50 million spectra in this time frame is foreseen. This is made possible by recent technical innovations in multi-fiber spectroscopy; specifically the development of the 'Echidna' concept at the AAO for positioning fibers using piezo-electric ball/spines. A 1m-class Schmidt telescope equipped with an Echidna fiber-optic positioner and suitable

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[1] http://www.aip.de/RAVE

spectrograph would be able to obtain spectra for over 20 000 stars per clear night.

In either version, the RAVE survey will represent a giant leap forward in our understanding of our own Milky Way galaxy, providing a vast stellar kinematic database, at least an order of magnitude larger than any other survey proposed for this coming decade. RAVE will offer the first truly representative inventory of stellar radial velocities for all major components of the Galaxy.

6. Summary and Conclusions

- Cosmological simulations are now sufficiently detailed to resolve galactic scales and to readily produce the main components of galaxies such as disks, bulges, bars, and stellar halos. However, as of now it is still unclear, whether the right mixture of different morphological structures can be reproduced; in particular the formation of pure disk components remains notoriously difficult.

- Numerical simulations are also capable of reproducing many of the observed scaling laws of galaxies, such as the the Tully-Fisher relation.

- Recent observational campaigns studying in detail the structure and kinematics of the Galaxy and M31 provide ample evidence that the formation history of galaxies is locked up in the stellar record and is still awaiting discovery.

Ultimately, the comparison between the small scale structure obtained in numerical simulations compared with those observed in neighboring galaxies has the potential to confirm the success of the "concordance" model by testing its detailed predictions on scales far removed from those used to tune its parameters. Should, however, some of the reported problems on small scales persist, they may even force the demise of the current paradigm of structure formation in the universe.

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