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PHYSICAL PROCESSES BEHIND THE MORPHOLOGICAL HUBBLE SEQUENCE

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RESUMEN

Presentamos una reseña de la formación y evolución de las galaxias haciendo énfasis en los factores físicos relevantes para entender el origen de la secuencia de Hubble. Nos concentramos en las predicciones del escenario jerárquico de Materia Obscura Fría (MOF) y su confrontación con las observaciones. Describimos los procesos de agregación de masa de los halos de MOF, los procesos en la materia bariónica atrapada por los halos, así como la formación y evolución de los discos y esferoides. Los aciertos y las debilidades de la teoría son analizados. La evolución de los discos parece implicar un proceso contínuo y extendido inducido por las condiciones cosmológicas iniciales, mientras que los esferoides derivan probablemente de eventos violentos en los cuales compiten varios procesos astrofísicos.

ABSTRACT

The study of formation and evolution of galaxies is reviewed, with emphasis on the physical factors which are important to understand the origin of the Hubble sequence. We concentrate on predictions of the hierarchical Cold Dark Matter (CDM) scenario and their confrontation with observations. The mass assembling of the CDM halos, the baryonic processes within them, and the evolution of disks and spheroids are described. The successes and shortcomings are discussed. Disk evolution seems to be a quiescent and extended process driven by the cosmological initial conditions, while spheroids are formed probably in violent events, where several astrophysical processes are competing.

Key Words: **GALAXIES: ELLIPTICALS — GALAXIES: EVOLUTION — GALAXIES: SPIRALS — COSMOLOGY: DARK MATTER**

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1. INTRODUCTION

The Cold Dark Matter (CDM) cosmological model, inspired by the inflationary theory, has triggered the development of a provocative *deductive* scenario of galaxy formation and evolution. According to this scenario, galaxies form within non-dissipative dark matter halos, which assemble hierarchically from primordial density fluctuations (White & Rees 1978). The deductive approach offers a valuable theoretical frame for interpreting the galaxy phenomena and motivates new confrontations between theory and observations. In parallel, from the observed properties of Milky Way (MW) and nearby galaxies, chemical and spectrophotometric evolutionary models allowed us to infer, by an *inductive* approach, fundamental aspects of galaxy evolution. More recently, the observation of galaxies at different redshifts is making it possible to trace directly the luminous, structural and dynamical evolution of whole populations of galaxies.

The question of how the Hubble morphological sequence originated and evolved in its complex relation with the environment is one of the most exciting challenges of extragalactic astronomy. The Hubble sequence (HS) of galaxies is based on a morphological classification, but several physical properties also change along this sequence (Roberts & Haynes 1994), a relevant morphological indicator being the bulge-to-disk ratio (Hubble 1936; Simien & de Vaucouleurs 1986). Therefore, it is natural to concentrate our attention on the physical nature of disks and spheroids, and on how galaxy structures do emerge in the context of a unified cosmological scenario.

While the evolution of disks appears gradual and extended in time, spheroids (elliptical galaxies and bulges) seem to concentrate their star formation activity upon a violent, early phase of their evolution. According to hierarchical galaxy formation schemes, most of the stars originated in disks, while subsequent processes of dynamical nature transformed some of these disks into spheroids. Nowadays, the increasing information of the high-redshift universe is opening new perspectives for the understanding of the formation of spheroids, its connection with ultra luminous infrared galaxies (ULIGs), quasars (QSOs), active galactic nuclei (AGNs), as well as for the interplay of galaxy formation with the intergalactic medium.

In this review our attention will be focused on the

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formation and evolution of disks and spheroids in the hierarchical CDM scenario. Some recent reviews on observational and evolution aspects of the HS can be found in Roberts & Haynes (1994), Ellis (1999, 2001), Freeman (1999), van den Bergh (2002). Previous reviews on the physical origin of the HS can be found in Silk & Wyse (1993) and Pfenniger (1996).

The plan of this review is first to discuss the origin and properties of the galactic dark matter halos, as well as the gas infall and galaxy formation processes within them (§§2 and 3). Then, the status of models of disk and spheroid formation in the hierarchical scenario and their comparison with observations will be presented in §§4 and 5, respectively. In §6 a sketch of the unified phenomenon of galaxy formation in the cosmological context is presented, and in §7 the concluding remarks as well as some perspectives for the future are enumerated.

2. DARK MATTER PROCESSES

In a CDM universe, the formation of cosmic structures is governed by gravitational processes. At large scales the influence of baryons is negligible. Starting from a Gaussian density fluctuation field with a given processed power spectrum, the gravitational clustering of the fluctuations is followed to the present epoch by means of cosmological N-body simulations, and the results are confronted with observations (for recent numerical results see e.g., Jenkins et al. 1998; Evrard et al. 2002). The completion of large surveys of galaxies and clusters of galaxies, the measurements of sub-degree anisotropies in the microwave background radiation, and the detection of cosmological SNe improved significantly our understanding of the large-scale structure and the mass-energy composition of the Universe (for a recent review see Guzzo 2002 and the references therein). The agreement between observations and the CDM predictions is remarkable (see Frenk, this volume). The "concordance" ΛCDM cosmological model (Bahcall et al. 1999) emerges as the favorite one. For this model, the universe is flat with the following approximate values of the cosmological parameters: $\Omega_{\rm bar} = 0.04$, $\Omega_{\rm CDM} = 0.26$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 0.9$, and $H_0 = 65 {\rm kms}^{-1}$ Mpc^{-1}. In this review, with the generic term CDM we will refer to the ΛCDM model.

At the scales of galaxies and clusters of galaxies, where high resolution is required in the simulations, an extensive work on formation, mass function, structure, and evolution of the CDM matter halos has been done in the last decade. Analytical and semi-analytical approaches, but mainly numerical N-body simulations, were used. The dark halos are the backbone of the galaxy formation models. Following, we discuss some results which appear relevant for the properties of galaxies:

i) The shape of the *mass function* of CDM halos is approximately similar to that of the observed Schechter luminosity function of galaxies (e.g., Press & Schechter 1974; Lacey & Cole 1993). The semi-analytical models show that the main problem is at the faint end of the luminosity function (e.g., Kauffmann et al. 1993; Cole et al. 2000; Somerville & Primack 1999); however, reionization and feedback may possibly solve the conflict (Benson et al. 2002a, see also this volume).

ii) The average *density profiles* of CDM halos are described typically by a universal two parameter profile, both depending ultimately only on the halo mass (Navarro, Frenk, & White 1997, hereafter NFW). Less massive halos tend to be more concentrated than the more massive ones. However, for a given mass, the halo density profiles show a scatter around the NFW profile. This scatter correlates with the halo mass aggregation history (MAH), in the sense that halos assembled earlier are more concentrated (Avila-Reese et al. 1998,1999; Wechsler et al. 2002). Some dependence on the environment has also been reported (but see Lemson & Kauffmann 1999). The CDM halos are too concentrated and their inner density profiles are cuspy, in apparent disagreement with observations, mainly the inner rotation curves of dwarf and LSB galaxies (Moore 1994; Burkert 1995; see also Bosma, de Blok, and Colín et al. in this volume). At galaxy-cluster scales, the inferred halo inner density profiles, under the uncertainties, typically are fitted by both the NFW and the pseudo-isothermal profiles. Observations seem to show that, from dwarf to galaxy-cluster scales, the central halo density is poorly dependent on mass, and the core radius increases roughly proportional to the maximum circular velocity $V_{\rm max}$ (Firmani et al. 2000, 2001). Figure 1 presents the approximate range of values of the halo central density and core radius vs. $V_{\rm max}$ inferred from observations. Another potential problem of the CDM halos is that the number of subhalos within MW-sized halos overwhelms the number of observed satellite galaxies by a large factor (Kauffmann et al. 1993; Klypin et al. 1999; Moore et al. 1999). Besides, the large population of satellite subhalos could have a dramatic effect on the dynamics of the galaxy disks (Moore et al. 1999; Colpi, Mayer & Governato 1999). Owing to the success of the CDM model at large scales, only minor modifications to the model has been proposed in order to solve these potential problems. For example,

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in a Warm Dark Matter (WDM) scenario with particle masses of $\sim 0.6-1$ KeV, the satellite velocity function in MW-sized halos is well reproduced, while at larger scales the predictions are similar to CDM (Colín et al 2000). However, the inner density profiles of galaxy-sized and larger halos are similar to their CDM counterparts; even the small subhalos show density profiles well fitted by the NFW profile, although with concentrations lower than predicted by CDM (Avila-Reese et al. 2001; Bode, Ostriker & Turok 2001). Conversely, self-interacting dark matter (SIDM) with a velocity-dependent cross sections, $\sigma_{DM} = 0.5-1.0\,(100\mathrm{kms}^{-1}/\mathrm{V_{max}})\,\mathrm{cm}^2/\mathrm{gr}$, produces inner halo density profiles in agreement with observations at all scales (Fig. 1), but the substructure remains similar to CDM (Firmani et al. 2001; Colín et al. 2002, see also this volume). The substructure problem may be actually alleviated by the reionization, which certainly has to be taken into account in the formation of dwarf galaxies (Bullock et al. 2000; Benson et al. 2002a).

iii) The *angular momentum* distribution in most of CDM halos seems to be well parametrized by a universal function, and the disks formed within them, assuming detailed angular momentum conservation, are roughly exponential (Bullock et al. 2001b). The global spin parameter λ has a lognormal distribution and is approximately independent of the cosmology, mass, and environment (e.g. Catelan & Theuns 1996). Two mechanisms for the origin of the halo angular momentum seem to compete: linear tidal torques and orbital angular momentum transfer of merging satellites (e.g., Peebles 1969; Vitvistkaya et al. 2002; Maller, Dekel & Somerville 2002). The role of angular momentum in formation of galaxies is crucial. More work should be done, for example, on the symmetry and degree of alignment of the angular momentum distribution in the halos (see van den Bosch et al. 2001 for recent results) and on the angular momentum dependence on environment.

iv) The hierarchical *mass aggregation history* (MAH) of CDM halos scatters around its average, because they emerge from a stochastic density field. On average, the less massive halos tend to assemble a given fraction of their mass at earlier epochs than the more massive halos (Avila-Reese et al. 1998). The halos may grow by a variety of merging regimes going from smooth mass accretion to violent major mergers (e.g., Salvador-Solé et al. 1998). This variety of merging regimes is relevant to the morphology of the galaxies formed within the halos. Cosmological simulations show that (i) most of the $z = 0$ galaxy-sized halos are not contained within larger halos nor have

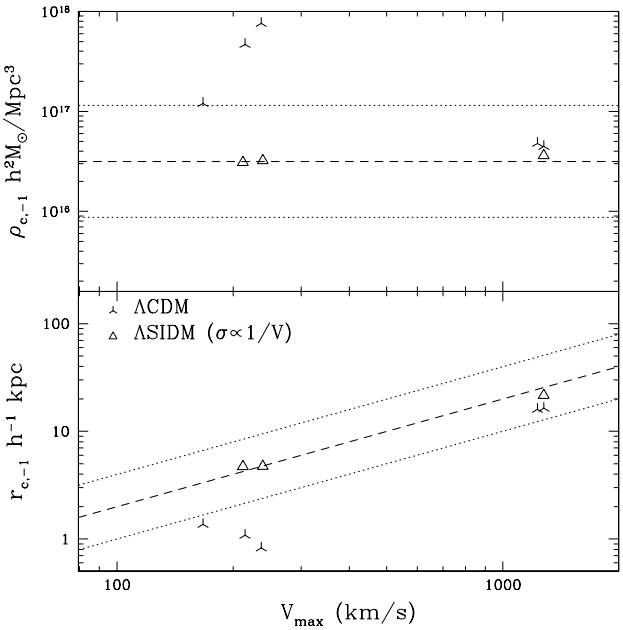

Fig. 1. Central density and core radius in this plot are defined as the density and radius where the halo profile slope becomes steeper than -1. The dotted lines encompass roughly the 2 σ dispersion of the observational inferences of $\rho_{c,-1}$ and $r_{c,-1}$ vs. V_{max} for dwarf and LSB galaxies and several clusters of galaxies (see Colín et al. 2002 for the source references). Squeletal and open triangles are high-resolution halo simulations for the ΛCDM and ΛSIDM models; the latter one is for a cross section inversely proportional to the relative velocity.

close massive companions, and that (ii) most of the mass of these halos has been aggregated by smooth accretion (Avila-Reese et al. 1999; Somerville & Kolatt 2000; Gottlöber et al. 2001). Nevertheless, the pair abundance and the major merger rate increase with z, and this increase is faster for cluster halos than for field halos (Gottlöber et al. 2001). The predicted major merging rates agree with those inferred from accurate statistics of galaxy pairs. From the fraction of normal galaxies in close companions (with separations less than 50 kpch^{-1}) inferred from observations at $z = 0$ and $z = 0.3$ (Patton et al. 2000, 2002), and assuming an average merging time of ~ 1 Gyr, we estimate that the major merging rate at the present epoch is $\sim 0.01\ \mathrm{Gyr}^{-1}$ for halos in the range of $0.1-2.0\ 10^{12}\mathrm{M}_\odot$, while at $z = 0.3$ the rate increased to $\sim 0.018\ \mathrm{Gyr}^{-1}$. These values are only slightly lower than predictions for the ΛCDM model, suggesting that the model can be used to predict the increasing merging rate at earlier epochs. The fact that at high redshifts the major merging rate is much higher than at the present epoch may be at the ba-

sis of early spheroid formation, as well as energetic phenomena like QSOs and submillimeter sources (see §§5 and 6).

Using cosmological N-body simulations, we have learnt much about the clustering and properties of collapsed CDM structures. Nevertheless, important details about the innermost, less resolved regions of dark halos, where just luminous galaxies form, as well as about the angular momentum, the MAHs and their dependences on the environment, remain still unexplored. On the other hand, the potential conflicts of CDM at small scales are still open. More observational and theoretical studies are necessary to understand the depth of these conflicts.

3. BARYON MATTER PROCESSES

Cosmological simulations including gas show that at $z = 0$ only $30 - 40\%$ of the universal baryon matter is within collapsed halos; the rest is in the form of warm-hot IGM in the filaments and voids (Davé et al. 2001). Recent observations tend to confirm this prediction (e.g., Manucci, this volume). Not all the gas trapped within the galactic halos ends up in the central galaxy: for large halos ($M \gtrsim 10^{12} M_\odot$) the cooling time may be longer than the Hubble time, while for small halos ($M \lesssim 10^{10} M_\odot$) a large fraction of gas may be expelled due to feedback. Owing to the combination of cooling and feedback, galaxies incorporate on average only half of the baryons originally trapped within halos (van den Bosch 2002). Therefore, for a universal fraction $\Omega_{\rm bar}/\Omega_{\rm CDM} \approx 0.15$, the actual fraction of matter trapped in galaxies, $f_{\rm gal}$, is only $\approx 0.15 \times 0.4 \times 0.5 \ = 0.03$.

The physics of baryons within the collapsing and merging dark matter halos is a highly complex process. In some cases, instead of radiative cooling, *turbulent dissipation in a multi-phase regime* (unexplored in detail yet) dominates. The process is further complicated by the gravitational fragmentation and consequent transformation of gas into stars. The energy and momentum input on gas from stars introduces a feedback. The feedback establishes a control and self-regulates the SF. The self-regulation may be either **(a)** at the level of the disk ISM, where, according to the nature of the feedback, a variety of regimes appear, ranging from stationary SF to bursting SF (e.g., Firmani & Tutukov 1994), or **(b)** at the level of the whole intrahalo medium, giving rise to a huge hot gas halo around the luminous galaxy (e.g., White & Frenk 1991; Benson et al. 2000). Models of galaxy evolution in the cosmological context used either case (a) for disks (Firmani et al. 1996, Firmani & Avila-Reese 2000; Avila-Reese & Firmani 2000; van den Bosch 2000) or case (b) (e.g., Kauffmann et al. 1993, 1999; Cole et al. 1994, 2000; Baugh et al. 1996).

Since dark halos have some angular momentum, during the smooth mass accretion phase, the dissipating gas falls until it reaches centrifugal equilibrium: disks are a generic prediction of the hierarchical scenario (Kauffmann et al. 1993). As the disk ISM is dense, highly dissipative and with shielding magnetic fields, the energy injection on gas is confined to a few disk scale heights (Avila-Reese & Vázquez-Semadeni 2001, and references therein). The lack of bright X-ray halos around spirals (Benson et al. 2000) reinforces the idea that case (a) rather than case (b) applies for disk galaxies. On the other hand, case (b) probably is working in spheroids where the low internal gas density makes dissipation inefficient. It seems also that cooling is more efficient than that calculated by simple approaches in the semi-analytic models (Toft et al. 2002). When the halo angular momentum is sufficiently low or the gas angular momentum loss is efficient, then highly concentrated disks may form. These disks are gravitationaly unstable and a spheroid may be produced by a secular process, which involves the formation and dissolution of a bar (Combes et al 1990; Norman et al. 1996; Merrifield & Kuijken 1999; Valenzuela & Klypin 2003).

As mentioned in §2, dark halos grow by a variety of merging regimes. Major mergers induce collisions between the central luminous galaxies. In this case, SF follows a bursting regime (Firmani & Tutukov 1994), feedback is very efficient, and the morphological Hubble type is strongly affected. Collisions between galaxies are indeed able to produce dynamically hot spheroids (Toomre & Toomre 1972; Schweizer 1982; Barnes 1988; Hernquist 1990, 1992). If the colliding galaxies are gas rich disks, then gas dissipation makes it possible to concentrate the spheroid up to the observed densities (Mihos and Hernquist 1994,1996; see also Hibbard and Yun 1999). Collisions between galaxies and secular formation from bar dissolution represent two competitive processes for the formation of spheroids.

Using the semi-analytical models, several authors extended the hierarchical merging of CDM halos to a merging picture of luminous disk/bulge/elliptical galaxy formation (e.g., Baugh et al. 1996; Cole et al. 2000). According to this picture, the driver of galaxy evolution, as far as concerns the HS, is the dark halo merging. Cosmological simulations indeed show the possibility of rapid galaxy morphological transformations due to intermittent changes of quiescent phases

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of disk accretion with violent phases of spheroid formation by major mergers (e.g., Steinmetz & Navarro 2002). However, cosmological simulations also show that most galaxies are formed actually by smooth accretion rather than mergers (Murali et al. 2000). This is in agreement with the predominance in number of disk galaxies in the local universe.

All these physical ingredients are involved in galaxy evolution, and are crucial to the understanding of the origin of the HS. It is now natural to concentrate our attention on the physics of disks and spheroids.

4. DISKS

A model aimed to study the physics and evolution of disk galaxies should include a self-consistent and local description of dark matter processes, and gas dissipation, infall, SF, stellar evolution, and feedback. Under the assumptions of (i) dominance of accretion rather than mergers, and (ii) detailed angular momentum conservation during gas infall, several authors have been able to reproduce the main properties and correlations of disk galaxies in the hierarchical CDM scenario. The former assumption is motivated by the fact that disks are dynamically fragile objects and collisions with other galaxies heat and thicken the stellar disk beyond the level observed at present (Tóth & Ostriker 1992). The latter assumption is argueable, and is currently among the key questions of disk formation models (see e.g., van den Bosch et al. 2002). Following, we discuss the main predictions of models of disk formation inside CDM halos. A seminal paper on this subject was that of Fall & Efstathiou (1980).

4.1. *Disk models at $z = 0$*

The *stellar surface density profile* is roughly exponential, but with an excess at the inner and outer regions (Dalcanton et al. 1997; Firmani & Avila-Reese 2000; Bullock et al. 2001a; van den Bosch 2002). The inner cusp may be crucial for the secular bulge formation. The surface density of the disks depends mainly on the spin parameter λ: the angular momentum drives the sequence from high surface brightness (HSB) to low surface brightness (LSB) galaxies. The surface density also depends on f_{gal}. Mainly due to the inside-out formation, the disks have *negative color index and metallicity gradients* in agreement with observations (Avila Reese & Firmani 2000; Boissier & Prantzos 1999, 2001).

The *rotation curves* are roughly flat. The shape of rotation curves depends on the disk surface density (Mo, Mao & White 1998; Firmani & Avila-Reese 2000). LSB galaxy models are dominated by the dark halo and even for the extreme HSB models, the CDM halo is competitive with the disk at the maximum rotation velocity. For the inner region of normal HSB galaxy rotation curves to be dominated by disk (maximum disk case), a soft core in the CDM halo is necessary (Avila-Reese et al. 2002; see also Salucci & Burkert 2000; Salucci 2001).

The slope of the infrared *Tully-Fisher relation (TFR)* is interpreted as a consequence of the mass-velocity relation of the CDM halos, determined in turn by the power spectrum of fluctuations (e.g., Mo et al. 1998; Avila-Reese et al. 1998, 1999; Steinmetz & Navarro 1999; Firmani & Avila-Reese 2000; Buchalter et al. 2001). The slope of the halo mass-velocity relation derived from theory is $\approx 3.2 - 3.4$, which agrees with the TFR slope in the infrared bands found by most observers (e.g., Gavazzi 1993; Giovanelli et al. 1997; Tully et al. 1998; Tully & Pierce 2000). After the formation of the disk and the stars within it, the zero point of the model TFR is slightly fainter than observations for the concordance ΛCDM cosmology (see Fig. 2), and is far too faint for the SCDM one. The introduction of soft halo cores improves the comparison with observations (Firmani & Avila-Reese 2000; Mo & Mao 2001). The N-body+hydrodynamical simulations predict a too faint zero point even for the ΛCDM model (e.g., Steinmetz & Navarro 2000), but this is mainly because the disks in these simulations are formed highly concentrated (angular momentum catastrophe), implying very peaked rotation curves.

Variations in f_{gal} and λ do not affect significantly the TFR. For a larger f_{gal}, the luminosity will be higher, but V_{max} also results larger. A smaller λ implies a more dominant disk component and therefore a larger V_{max} for a given mass; however, the SF efficiency is higher in such a way that the stellar mass (luminosity) for a fixed baryonic mass will be also larger (Firmani & Avila-Reese 2000). This is the way we interpret *why the TFRs of LSB and HSB galaxies are similar and why the residuals of the TFR do not correlate with the residuals of the magnitude-radius relation* (Courteau & Rix 1999). We also find that the main source of intrinsic scatter in the TFR derives from the scatter in the halo concentrations due to the stochastic nature of the MAHs (Eisenstein & Loeb 1996); the average scatter we measure is ~ 0.3 mag, close to the observational estimates.

If bulges are modeled as the gravitationally unstable stellar disk region (secular scenario), then higher surface brightness galaxies have larger bulge-to-disk ratios (van den Bosch 1998; Avila-Reese & Firmani 2000). The models reproduce the *main cor-*

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relations along the disk HS: the higher the SB and the redder the disk, the larger the bulge-to-disk ratio and the lower the disk gas fraction. Bulges formed secularly seem to be in agreement with observations, at least for late-type galaxies (see for a review Wyse et al. 1997).

Models can be tested even in the *solar neighborhood*. For a MW fiducial model (based on the statistically most probable cosmological MAH), the predicted evolution of the SF rate in the solar neighborhood agrees within the uncertainty with the evolution derived from the HR diagram provided by the Hipparco satellite (Hernández, Avila-Reese & Firmani 2001). On the other hand, chemical and photometric models, starting from the observed distributions in the MW, infer infall, structural and SF conditions similar to those expected from the hierarchical scenario (e.g., Boissier & Prantzos 1999; Prantzos, this volume). However, the inner dynamics again reveals a conflict: the CDM halo concentrates too much mass in the central regions in such a way that the shapes of the model and observed MW rotation curves do not agree. A soft core of size as inferred from observations of LSB and dwarf galaxies eliminates the discrepancy.

4.2. *Disk evolution*

The sizes of disks in the hierarchical scenario decrease significantly with redshift (Mao, Mo et al. 1998; Giallongo et al. 1999; Avila-Reese & Firmani 2001). Interpretation of data regarding disk size and SB evolution is controversial. Roche et al. (1998) using *HST* data concluded that since $z \approx 1$, spirals suffered both size and luminosity evolution, while Simard et al. (1999) concluded that data show no size evolution. Bouwens & Silk (2002) show that the SB distribution of disk galaxies evolves strongly. They re-analyzed the data of Simard et al. introducing new corrections for SB selection bias and found size evolution in the data. The question is open.

The SF history of disk models is driven by both the gas accretion rate determined by the MAH, and the disk surface density determined by λ (Avila-Reese & Firmani 2001). Merging could also play a relevant role (Kauffmann et al. 2001). The increase of the SF rate (and $B-$band luminosity) with z inferred from observations of normal spirals (e.g., Lilly et al. 1997; Abraham et al. 1999) is slightly steeper than our model predictions. The integral colors of the models become bluer toward the past, in agreement with observations.

The evolution of the TFR is a highly debated topic and apparently it depends on whether the studied sample is dominated by small or normal spirals. Model predictions show that the slope of the $B-$band TFR decreases and the zero point becomes brighter at higher z's (Fig. 3; see also Avila-Reese & Firmani 2001). Comparing with the observed sample of Vogt et al. (1997) at $< z >= 0.54$, the agreement in the zero point is reasonable (for the ΛCDM cosmology). On the other hand models show that the zero-point of TFR in the near infrared band evolves in an opposite way: at $z = 1$ it is fainter than at $z = 0$. (see Fig. 3) This can be understood taking into account that galaxy evolution traces halo evolution: the halo mass (scaling with the disk mass traced by the infrared luminosity) decreases significantly from $z = 0$ to $z = 1$, while V_{max} decreases only moderately. In the case of the $B-$band, since the accretion rate peaks at $z \sim 1-2$, the star formation rate, and therefore L_B, are (slightly) higher at these reshifts. The evolution of the comoving number density of halos is connected with the TFR; a deficit of bright (massive) galaxies at larger redshifts translates into a dimming of the zero-point of the infrared TFR (Bullock et al. 2001a). The evolution of the TFR up to high redshifts ($z \sim 3$) can be a po-

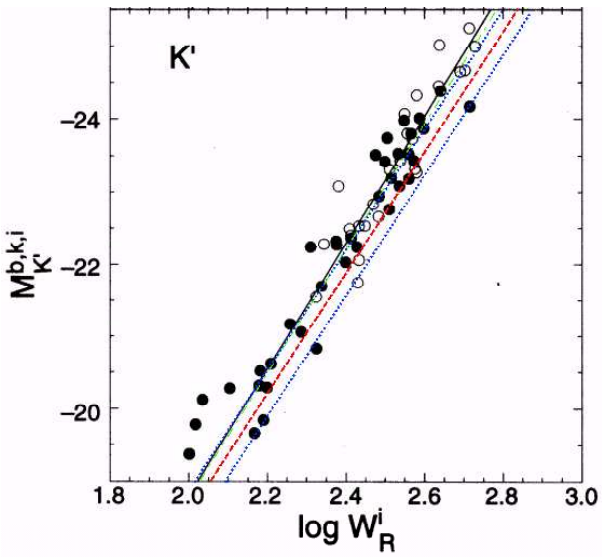

Fig. 2. Tully-Fisher relation in the band K as inferred by Tully et al. (1998). Solid line is the linear regression to the data. Dashed line is the TFR from models of galaxy evolution in the ΛCDM cosmogony (Firmani & Avila-Reese 2000); detailed angular momentum conservation was assumed. Dotted lines correspond to the model scatter ($\pm 1-\sigma$ dispersion). The dot-dashed lines is the TFR for the same models, but introducing a soft core in the halos to be in accord with the rotation curve inner shapes of LSB and dwarf galaxies. The agreement with observations is excellent. The TFR is an imprint of the density fluctuation power spectum.

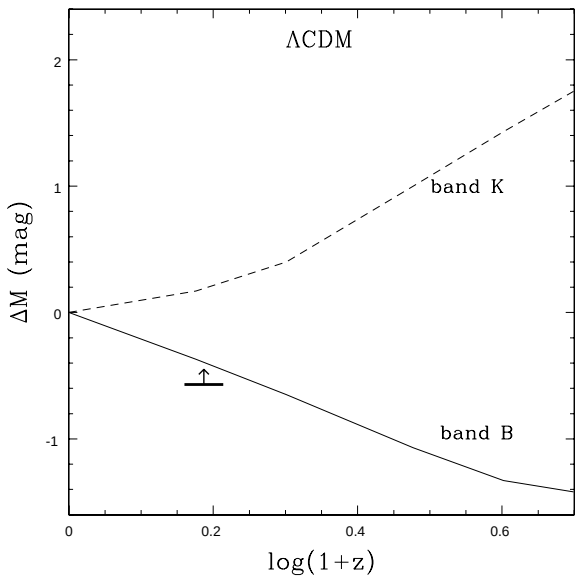

Fig. 3. Evolution of the model TFR in the bands B and K. The slopes at different redshifts were fixed to the corresponing ones at $z = 0$. The zero-point becomes brighter at higher redshifts in the band B, while in the band K the behaviour is opposite (see text). The arrow indicates the lower limit inferred from observations by Vogt et al. (1997); we have passed their data to the ΛCDM cosmology used here.

tentially powerful discriminator of galaxy formation models (Buchalter, Jiménez & Kamionkowski 2001).

4.3. *Drivers of the disk Hubble sequence*

The main properties, correlations and evolution features of disk galaxies formed within CDM halos, under the assumption mentioned at the beginning of this section, arise from the combination of three cosmological factors and their statistical distributions: the *virial mass*, the *MAH*, and the *spin parameter* λ. The former determines the scale. The latter ones determine the SF history and the intensive properties, and are at the basis of the disk HS correlations, suggesting a biparametrical nature for this sequence (Avila-Reese & Firmani 2000). Observations tend to confirm this biparametrical nature (e.g, de Blok & McGaugh 1997). The MAH drives the gas infall rate, which determines mainly the galaxy color indexes. The λ parameter determines mainly the disk SB, and strongly influences the rotation curve shape and the bulge-to-disk ratio (secular bulge). The mass galaxy fraction, f_{gal}, which influences some disk properties, is an astrophysical parameter determined mainly by the halo gas dissipation and feedback efficiencies; it may vary from galaxy to galaxy, but its value on average is around 0.03 (see §3). The shapes of the rotation curves and the SB distribution are better reproduced jointly just for this value (Avila-Reese et al. 2002).

An important ingredient, which begins now to be included in the CDM models of disk evolution, is the dynamics related to bars, spiral arms and minor mergers (e.g., see the contributions by Valenzuela, Athanassoula, Curir, Bertschik and others in this volume). This ingredient, highly connected to the main disk properties and processes described above, is at the basis of the "showy" disk morphological signatures, which characterize the tuning fork of the disk HS, and may play some role in the morphological transformation due to secular processes.

5. SPHEROIDS

In spite of their simple shape, spheroids reveal a very complex nature. Some memory of their formation lies in their dynamical structure and stellar population. The spheroid complexity is strengthened by the systematical presence of super massive black holes (SMBHs) at their nuclear regions, with rather well defined correlations between the SMBH mass and the spheroid luminosity or velocity dispersion (Magorrian et al. 1998; Ferrarese & Merrit 2000; Gebhardt et al. 2000), and the bulge concentration (Graham et al. 2001; Graham, this volume). AGN and QSO activity seem to be intimately associated with SMBHs. On the other hand, observations reveal that the ultra high luminosity infrared galaxies (ULIGs) show evidence of recent galaxy collisions (Sanders and Mirabel 1996); therefore ULIGs may also be linked to the formation of spheroids.

5.1. *Relevant observational properties and correlations*

Radius, velocity dispersion and surface brightness are related by the fundamental plane (FP) (Bender et al. 1992), which is basically related to the virial theorem and to the M/L ratio inside the effective radius. The use of NIR photometry (Pahre 1998, Pahre et al. 1998a) reduces the effects of the SF history on the M/L ratio and traces the gravitational contribution of dark matter. A homology breaking (dynamical [Busarello et al. 1997; Graham & Colless 1997] and/or photometric [Bertin et al. 2002]), connected to the spheroid formation and evolution, introduces effects difficult to evaluate. The observed evolution of the FP intercept up to $z = 0.4$ suggests a passive evolution for the stellar population, with a formation redshift of $1.0 - 1.5$ (Pahre et al. 1998b, Treu et al. 2001). The change in slope with z is not clear, but the possibility that massive ellipticals could be younger than the less massive ones seems

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

to be ruled out. The scatter of the FP does not show any correlation with metallicity, redshift (age effect), or environment (field or clusters).

The brightness of giant spheroids decreases with size (Kormendy relation, KR; Kormendy 1977; Pahre et al. 1998a), implying that the mean density of spheroids decreases with their mass. It is interesting to note that a similar tendency is shown by dark virialized halos in a hierarchical cosmogony. However, at present it is not clear if the density-mass relation of galaxy spheroids can be explained in terms of the dark halo properties alone or by other processes related to the gas hydrodynamics or to the SF. The observed luminosity evolution agrees with the passive evolution of a star population formed at $z \gtrsim 1$. The Faber-Jackson relation (FJR) may be understood as a combination of the FP and the KR.

The Mg_2-velocity dispersion relation shows mainly how the metallicity increases with the mass. The color-magnitude relation involves both metallicity and age. The evolution up to $z = 1$ of the zero point and of the scatter of this relation suggests a formation redshift $\gtrsim 2$ for most of the field and cluster ellipticals (see Peebles 2003) (even if some uncertainty derives from the sample selection).

From the shape of their isophotes, elliptical galaxies are divided into disky and boxy. It has been suggested that the origin of this dichotomy is related to the mass ratio of the merged disk progenitors (Naab et al. 1999). High resolution observations of the central region of luminous, slowly rotating boxy ellipticals (mainly members of clusters), identify a shallow core, while in faint rapidly rotating disky ellipticals (mainly field galaxies), peaked power-law density profiles were found (Faber et al. 1997; Carollo et al. 1997).

5.2. *Theoretical aspects*

The unification of the physics implied in all of these properties and phenomena is an appealing challenge. Gas-rich mergers (e.g. two disks), besides heating and thickening the preexisting disk stellar population, removes angular momentum from gas and allows the gas to concentrate further in the center. The low angular momentum gas, which dissipates probably in a turbulent regime, will form a compact disk, where stars are born in a high density environment, rich in dust and molecules. An intense burst of star formation takes place driven by a radiation pressure (Eddington) self-regulation, while the bulk of UV radiation is converted to FIR by dust (Firmani & Tutukov 1994). This phase may be identified as an ULIG. In the central region gas reaches very high density, probably due to a gravothermal catastrophe. This condition favors the growth of the preexisting black hole through an Eddington (Silk & Rees 1998; Fabian 1999; Nulsen & Fabian 1999; Blanford 1999, see also Merrifield et al. 2000) or even super-Eddington regime (Begelman 2001). The accretion, hidden by gas and dust, swallows only a minor fraction of the infalling gas. When the SMBH reaches a critical mass, the gas outflow becomes catastrophic and most of the gas is expelled. Probably, a small fraction of gas is retained in an accretion disk which continues to feed the SMBH during a few millions years (Burkert & Silk 2000). The expulsion of gas ends the FIR emission phase and allows the AGN to appear in all its brightness. The QSO phase lasts the time sufficient to exhaust any residual gas feeding. After this ultra-high luminous phase finishes, the SMBH enters in a dormant phase in the heart of the stellar spheroid, which will appear as a disky elliptical galaxy with a power law inner density profile.

This scenario gives some idea about the role of merging on the formation of spheroids. However, other astrophysical processes may influence the further evolution of spheroids. Gravitation and cooling push gas to inflow. As shown by Ciotti et al. (1991), the gas heating due to SN Ia is enough to refund the energy lost by cooling and to produce supersonic galactic winds, at least in the early phases after the SF burst. As the SN Ia rate decreases with time, the wind changes to an outflow regime. Thereafter, if the spheroid is sufficiently massive, a cooling catastrophe in the inner region converts outflow into inflow. Once inflow is established, the fate of gas in the inner region is uncertain. Low mass SF driven by thermal instabilities can drop out gas from the flow (Mathews & Brighenti 1999a, 1999b), otherwise infalling gas starts to feed the central SMBH, which enters into an AGN phase (Ciotti & Ostriker 1997, 2001). In the latter case, the gas energy balance is strongly influenced by the AGN energy injection. Gas inflow at some time is suddenly converted to an outflow, while SMBH returns to its dormant phase. At this point the cycle outflow-inflow-AGN repeats again. This conjecture, based on cooling flow, identifies an AGN driving mechanism alternative to the one based on major mergers. The cooling-flow driving mechanism for AGN finds some support in the observations of Schade et al. (2000) and Dunlop et al. (2001), who did not see strong evidence of major merging in their sample of AGN host spheroids. Several aspects of this process have to be studied taking into account, besides the stellar mass loss, the gas accretion predicted by the hierarchical scenario.

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

Several pieces of evidence support the idea that ULIGs represent the connection between mergers and the dust enshrouded formation of spheroids and AGNs. Even if ULIGs at present are rare systems and their contribution to the cosmic energy budget is negligible, at high redshift this contribution grows and becomes dominant (similar to AGNs) (Sanders and Mirabel 1996; Krishna & Biermann 1998; Lilly et al. 1999; Dunlop et al. 2001; Granato et al. 2001). Most ULIGs show evidence of strongly interacting disk galaxies. The FIR luminosity increases with decreasing projected nuclear separation. A double nucleus is present in the majority of "cool" systems ($f_{25}/f_{60} < 0.2$), while a single nucleus is more frequent in "warm" systems. The fact that ULIGs represent ellipticals in formation is supported by the evidence that these objects fall near the FP of disky ellipticals (Genzel et al. 2001).

The sequence: merger between disk galaxies $\Rightarrow$ "cool" ULIG $\Rightarrow$ "warm" ULIG $\Rightarrow$ "IR excess" QSO $\Rightarrow$ QSO, is supported by the following arguments (Sanders 2001; Kim et al. 2002; Veilleux et al. 2002). A gradual transition from FIR to UV dominated spectral energy distribution (from "cool" to "warm") is accompanied by the appearance of a "big blue bump" (characteristic of optically selected QSOs) and nuclear superwinds. QSOs with FIR excesses (in transition from "warm" ULIGs) appear related to "disturbed" hosts, while E-like ULIGs and AGNs seem more likely to lie in hosts of similar masses. Hard X-rays will provide more information about the SMBH growth in the ULIG nuclei (Fabian 1999; Wilman et al. 2000).

This scenario is consistent with a simple demographic argument. From *HST*, Lilly et al. (1996) estimated a local blue luminosity density of $10^7 L_\odot/Mpc^{-3}$ Assuming $< M/L_B > \cong 14 M_\odot/L_\odot$ (see Dwek et al. 1998), the luminous matter density is then $1.4\ 10^8 M_\odot Mpc^{-3}$. If about half of the stars are assumed to be in spheroids, their mass density is then $7\ 10^7 M_\odot/Mpc^{-3}$ and the mass density in SMBHs will be $4\ 10^5 M_\odot Mpc^{-3}$, where the ratio $M_{SMBH}/M_{SPH} = 0.006$ has been assumed (Magorrian et al. 1998). The efficiency of mass converted in FIR during a star burst (Firmani & Tutukov 1994) is $5.3\ 10^{-4}$, then the FIR energy density produced by the star bursts of the spheroids is $4\ 10^4 M_\odot Mpc^{-3}$. Assuming an efficiency of 0.1 for the energy produced by the SMBH accretion, the energy density derived from this process is $4\ 10^4 M_\odot Mpc^{-3}$, an amount similar to the one derived from spheroids. The sum of both agrees with the total FIR energy density of $10^5 M_\odot Mpc^{-3}$ obtained by Dwek et al. (1998) in the DIRBE experiment.

A further argument supporting this scenario is given by Granato et al (2001). According to them, the spheroid formation rate, derived from the observed QSO luminosity function, leads to the observed spheroid number density at present. The anti-hierarchical baryonic collapse scenario of Granato et al. is consistent with the FIR source counts, the nature of Ly Break Galaxies (LBGs) and the chemical evolution of spheroids and QSOs. The SF in spheroids, correlated with the QSO luminosity function, shows that its bulk of activity happens at $z \gtrsim 2$.

The previous scenario is based on some important elements. (i) Gas infall has to reach very high density at the radius of BH influence in order to produce a sufficient BH growth. (ii) The SMBH is formed by a self-regulation mechanism that determines its final mass and induces a natural expulsion of gas which reduces suddenly the optical depth. (iii) The bulk of SF and AGN activity is strongly enshrouded by gas and dust.

If a collision occurs between two gas-poor stellar disks the remnant is not sufficiently dense to be identified with a real spheroid (Hernquist 1992). The presence of bulges in the progenitors plays an important role leading to a central dense spheroid comparable to the observed bulges (Hernquist 1993). The two SMBHs of the progenitors will coalesce spiralling-in towards the center by dynamical friction and gravitational wave emission, creating here a shallow stellar core similar to the ones observed in boxy elliptical galaxies (Makino & Ebisuzaki 1996; Quinlan 1997; Quinlan & Hernquist 1997; Milosavljevic et al. 2002).

6. THE HUBBLE SEQUENCE IN THE HIERARCHICAL COSMOGONY

In the previous sections we have pointed out several processes which intervene in the evolution of luminous galaxies. Summarizing, the first step in galaxy formation is the assembling of the dark matter halos, which may happen either quiescently or violently, depending mostly on the environment. In the former case, the gas trapped inside the halos dissipates (radiatively and turbulently), infalls to the center and forms an inside-out disk in centrifugal equilibrium with a surface density that depends mainly on the halo spin parameter. SF in disks is expected to be stationary and self-regulated by feedback and turbulent dissipation. In this case, the main drivers of the SF history are the gas infall and the angular momentum. Both of them are tightly related to the cosmological conditions. Some disks may suffer further morphological evolution due to

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

internal gravitational instabilities (spiral arms, bars and bulges).

However, the strongest changes are expected when violent major mergers occur: the stellar disk is heated and gas angular momentum is transferred, leading to the formation of spheroids and SF bursts. In this phase ULIGs and AGNs can appear. The products of galaxy collisions depend on the gas fraction, the stellar disk-to-bulge ratio and the dynamics of the encounter (Barnes & Hernquist 1991, 1996; Miho & Hernquist 1994, 1996; Barnes 2002). Numerical simulations show that a wide range of final products can be obtained, depending on these parameters. Nevertheless, the stellar component is almost always heated and thickened, acquiring the structure of a spheroid. The gas that suffers strong shocks transfers its angular momentum, and may originate a bulge. The gas that has not been involved in strong shocks retains a large amount of angular momentum and can feed an extended disk. Accretion from the environment supplies the spheroid/disk system with further angular-momentum-rich gas. The ultimate fate of gas is to be converted into stars. When the gas surface density is sufficiently high, the disk stellar population is practically coeval to the bulge, but as the gas surface density is lower, the slower is the SF rate.

In the hierarchical framework, the major merging rate is easily estimated by the extended Press-Schechter formalism or by N-body simulations (e.g., Gottloeber et al. 2001) and, for a given mass, is increasing with z. Multiplying the merging rate by the halo mass function at different z's, one obtains that the merging rate density (per unit of volume) for halos with masses smaller than $10^{13}M_{\odot}$ has its maximum at $z > 1$; for halos in clusters, the maximum is shifted to earlier epochs. Therefore, most of spheroids, upon the understanding that they arise from major mergers, are born at high redshifts, when galaxies are still gas rich. The smaller fraction of major mergers at late epochs occurs mainly between gas-poor galaxies with an important spheroidal component. Around the spheroid a disk grows by gas accretion according to the conditions of the environment and by the energy feedback of the spheroid, the bulge-to-disk mass ratio being an indicator of the Hubble type. When the spheroid is more massive than the disk, we have an elliptical or S0 galaxy. The lack of a massive disk in these cases may be due to the facts that *(i)* the merger has occurred recently, *(ii)* the gas accretion has been inhibited, or *(iii)* the environment is poor in gas. The existence of field elliptical galaxies with an old stellar population may be indicative of conditions that inhibit the formation and growth of a disk.

Using semi-analytic modelation and taking into account many of the physical processes mentioned above, Cole et al. (2000) have made predictions about the morphology mixing of galaxies and the dependence on the environment. Their models reproduce the relative number of E+S0 galaxies. However, concerning the age of spheroids, the situation is not so clear. Their predicted colour-magnitude relation for ellipticals in clusters is significantly flatter than that observed at bright magnitudes. Benson et al. (2002) have compared the same models with samples of field spheroidal galaxies with redshifts up to two. Models reveal some difficulty predicting the observed red population of E+S0 galaxies, while on the blue side the agreement is satisfactory. Colours reflect only approximately the ages of old spheroids. The ages of elliptical galaxies derived by different observational methods, such as those mentioned in section 5.1, are difficult to reconcile with the model predictions. Again, the situation could be alleviated if gas accretion and disk growth around spheroids would be inhibited (item (ii) above), in this way allowing some of the spheroids to evolve with a negligible SF activity. A careful comparison between models and observations of the relation between the intrinsic colours of the disk and the Hubble type should be of some relevance. In fact, a growing disk around a spheroid would evolve inside-out from blue to red while the bulge-to-disk ratio decreases; however, this situation depends on the physical conditions created by the collision as well by gas accretion and the intense feedback.

Back to galaxy collisions, it should be noted that its stochastic nature (as well as the extended redshift range of spheroid formation) contribute to the scatter of the FJR and KR, and possibly of the FP. While the scatter of TFR is a faithful product of the stochastical properties of the primordial density fluctuations (§4.1), the scatters of the spheroid scaling relations (FJR, KR, FP) are further increased by the astrophysical processes in which they have been involved (collisions, feedback).

6.1. *Connecting spheroid formation with QSOs*

The scenario described above opens the possibility to understand the physics of the HS, its dependence on the environment, the nature of peculiar elliptical galaxies with extended low surface density gaseous disks, as well as the connection with high redshift objects like QSOs and submillimeter sources.

QSOs provide now an important probe up to

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

$z \simeq 6$. Unfortunately, their lifetime and their connection with the host galaxy are still rather uncertain. An approach to the bulge-AGN evolution, in the context of the hierarchical scenario, has been proposed by e.g., Cattaneo et al. (1998), Cattaneo (1999, 2002), Kauffmann & Haehnelt (2000), and Wyithe & Loeb (2002). In these semi-analytical models, several assumptions and prescriptions are used to calculate the gas fractions in the merging disks (related to gas infall and SF) and the lifetime of QSOs. The models are able to reproduce roughly the ratio $M_{\rm SMBH}/M_{\rm bulge}$ and the evolution of the QSO luminosity function. The major difficulty arises at the low redshift side: the observed QSO population decreases dramatically since $z \sim 2$ to $z = 0$, while the merging rate decreases only a little. Cavaliere & Vittorini (2000) have studied this problem. An important fact to take into account is that the gas fraction decreases in galaxies with time. Furthermore, since SF in the inner disk regions is faster than at the periphery, the low angular momentum gas —which feeds the SMBH— is exhausted at a rate higher than the average. Using complete galaxy evolutionary models (e.g., Firmani & Avila-Reese 2000), this effect could be included into the QSO models to explain the luminosity evolution of QSOs at low z's. Another interesting aspect has to do with the multipliciy of processes able to activate SMBH. While it is reasonable to imagine that at early times QSOs have been activated mainly by major mergers, later on other processes besides mergers may become competitive in the inner region of a galaxy to stimulate a gas inflow and a SMBH feeding. The environment seems to be a key ingredient. Observations show that QSOs were more clustered at high redshifts than at low ones.

7. CONCLUDING REMARKS

The study of galaxies is not anymore only a "taxonomical" task. We are arriving now at a "genetical" level of their understanding, which opens the possibility to explain their diversity, in particular the origin of the HS. A relevant question emerges: is the origin of the HS dominated by cosmological conditions (nature) or by ulterior astrophysical processes (nurture)? The inductive approach has been particularly useful for exploring the latter item. A key aspect is the identification and the interconnection of the astrophysical processes that drive changes in the Hubble type, as well as the identification of observable fossil records of the different evolutionary phases. Models of spectrophotometric, chemical and dynamical evolution are the instruments which helped to reconstruct the past history from the observed fossil records. Most of the results from studies related to the inductive approach showed the necessity to connect galaxy evolution to external conditions. These conditions can be given by a cosmological scenario of structure formation.

The success of the inflationary CDM cosmology has pushed researchers to explore their ultimate consequences regarding galaxy formation (deductive approach). The predictions of models and simulations are encouraging; the hierarchical CDM model offers an invaluable theoretical background for understanding galaxies. The formation and evolution of disk galaxies within the CDM halos (§2) has been modeled with a minimum of free astrophysical parameters (§4). Therefore, the confrontation between theory and observations is particularly promising in this case. It seems that most of the properties and correlations of disk galaxies, including the correlations along the HS, are strongly linked to the initial conditions of the hierarchical CDM cosmology. A potential problem of the inside-out disks is their rapid size evolution, which could not be confirmed by high-redshift observations. More detailed comparisons of models and observations are needed at all the levels. They will allow to trace some properties of the early universe, as well as to infer the nature of the mysterious dark matter. As a result of some of these comparisons, galaxy-sized CDM halos seem to be too cuspy and with too much substructure. If the dark particles are assumed with some self-interacting properties or warm instead of cold, then the agreement with observations improves (§2).

The situation concerning spheroids is more complex than for disks. The age of the isolated spheroids and the details of the disk growing around the bulges are among the issues which keep open the debate about the congruency of the hierarchical cosmogony regarding spheroid formation. While the backbone of spheroid formation might be again the dark matter processes (major mergers mainly), complex astrophysical processes (e.g., non-stationary SF, strong feedback and cooling, dynamical processes, angular momentum transfer, SMBHs, gas outflow-inflow phenomena, etc.) make difficult the definition of an unambiguous evolutionary sequence. For spheroids, the astrophysical processes seem to be dominant. As has been emphasized by Renzini (1994), to reveal the complexity of galaxy evolution the deductive approach has to go necessarily together with the inductive one.

Great perspectives are open for further research in galaxy formation and evolution. A better understanding of all kinds of astrophysical processes in-

volved in the evolution of galaxies is crucial. Star formation, hydrodynamics and feedback are among the most relevant, in particular, for spheroids. A better modelling of the luminous objects which form within the dark halos, will allow us to use the observational properties of galaxies to trace the physical conditions of the early universe and dark matter. From the astrophysical side, the connection of spheroid formation to ULIGs, submillimeter sources and QSO-AGN phenomenon is an appealing problem. The interplay of galaxy evolution with the IGM is also an important avenue of research.

As Ivan King said sometime ago, *the main challenge is reserved for those who obtain results linking theory and observations; they are the astronomers.*

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Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

REFERENCES

Abraham, R.G., Ellis, R.S., Fabian, A.C., Tanvir, N.R., & Glazebrook, K. 1999, MNRAS, 303, 641
Avila-Reese, V., Firmani, C. & Hernández, X. 1998, ApJ, 505, 37
Avila-Reese, V., Firmani, C., Klypin, A., & Kravtsov, A., 1999, MNRAS, 309, 507
Avila-Reese, V., & Firmani, C. 2000, RevMexA&A, 36, 23
——— 2001, RevMexA&A (SC), 10, 97
Avila-Reese, V. & Vázquez-Semadeni, E. 2001, ApJ, 553, 645
Avila-Reese, V., Colín, P., Valenzuela, O., D'Onghia, E., & Firmani, C. 2001, ApJ, 559, 516
Avila-Reese, V., Firmani, C., & Zavala 2002, in ASP Conf. Series, 282, Galaxies: the Third Dimension, eds. M. Rosado, L. Binette & L. Arias, 137
Bahcall, N.A., Ostriker, J.P., Perlmutter, S. & Steinhardt, P.J. 1999, Science, 284, 1481
Barnes, J.E. 1988, ApJ, 331, 699
——— 2002, MNRAS, 333, 481
Barnes, J.E. & Hernquist, L. 1991, ApJ, 370, L65
——— 1996, ApJ, 471,115
Baugh, C.M., Cole, S., & Frenk, C.S. 1996, MNRAS, 283, 136
Begelman, M.C. 2001, ApJ, 551, 897
Bender, R., Burstein, D. & Faber, S.M. 1992, ApJ, 399,462
Benson, A.J., Ellis, R.S., & Menanteau, F. 2002, MNRAS, 336, 564
Benson, A.J., Bower, R.G., Frenk, C.S., & White, S.D.M. 2000, MNRAS, 514, 357
Benson, A.J., Lacey, C.G., Baugh, C.M., Cole, S. & Frenk, C.S. 2002a, MNRAS, 333, 156
Benson, A.J., Frenk, C.S., Lacey, C.G., Baugh, C.M. & Cole, S. 2002b, 333, 177
Bertin, G., Ciotti, L., & Del Principe, M. 2002, å, 386, 149
Blandford, R.D. 1999, in ASP Conf. Series 182, Galaxy Dynamics, eds. D.R. Merritt, M. Valluri & J.A. Shelwood, 87
Boissier, S. & Prantzos, N. 1999, MNRAS, 307, 857
———. 2001, MNRAS, 325, 321
Bouwens, R.J., & Silk, J. 2002, ApJ, 568, 522
Buchalter, A., Jimenez, R. & Kamionkowski, M. 2001, MNRAS, 328, 520
Bullock, J.S., Kravtsov, A.V. & Weinberg, D.H. 2000, ApJ, 539, 517
Bullock, J.S., Dekel, A., Kolatt, T.S., Primack, J.R., & Somerville, R.S. 2001, ApJ, 550, 21
Bullock, J.S. et al. 2001, ApJ, 555, 240
Burkert, A. 1995, ApJ, 477,L25
Burkert, A., & Silk, J. 2001, ApJ, 554, L151
Busarello, G., Capaccioli, M., Capozziello, S., Longo, G., & Puddu, E. 1997, A&A, 320, 415
Carollo, C.M., Franx, M, Illingworth, G.D., & Forbes, D.A. 1997, ApJ, 481, 710
Catelan, P., & Theuns, T. 1996, MNRAS, 282, 436
Cattaneo, A., Haehnelt, M.G., & Rees, M.J. 1999, MNRAS, 308, 77
Cattaneo, A. 2001, MNRAS, 324, 128
Cattaneo, A. 2002, MNRAS, 333, 353
Cavaliere, A., & Vittorini, V. 2000, ApJ, 543, 599
Ciotti, L., D'Ercole, A., Pellegrini, S., & Renzini, A. 1991, ApJ, 376, 380
Ciotti, L., & Ostriker J. 1997, ApJ, 487, L105
——— 1997, ApJ, 551, 131
Cole, S., Aragon-Salamanca A., Frenk C.S., Navarro J., & Zepf S. 1994, MNRAS, 271, 781
Cole, S., Lacey, C.G., Baugh, C.M., & Frenk, C.S. 2000, MNRAS, 319, 168
Colín, P., Avila-Reese, V., & Valenzuela, O. 2000, ApJ, 542, 622
Colín, P., Avila-Reese, V., Valenzuela, O., & Firmani, C. 2002, ApJ, 581, 777
Colpi, M., Mayer, L., & Governato, F. 1999, ApJ, 525, 720
Combes, F., Debbasch, F., Friedly, D., & Pfenniger, D. 1990, A&A, 233, 82
Courteau S., & Rix H.W. 1999, ApJ, 513, 561
Dalcanton, J.J., Spergel, D.N., & Summers, F.J. 1997, ApJ, 482, 659
Davé, R. et al. 2001, ApJ, 552, 473
de Blok, W.J.G., & McGaugh, S.S. 1997, MNRAS, 290, 533
Dunlop, J.S., et al. 2001, astro-ph/0108397
Dwek, E. et al. 1998, ApJ, 508, 106
Eisenstein, D.J., & Loeb, A. 1996, ApJ, 459, 432
Ellis, R.S. 1999, in "Cosmological Parameters and the Evolution of the Universe", Ed. Katsuhiko Sato (Dordrecht, Boston: Kluwer Academic), 107
——— 2001, Lectures given at the XIth Canary Islands Winter School of Astrophysics "Galaxies at High Redshift" (astro-ph/0102056)

Evrard, A.E. et al. 2002, ApJ, 573, 7
Faber, S.M. et al. 1997, AJ, 114, 1771
Fabian, A.C. 1999, MNRAS, 308, L39
Fall, S.M. & Efstathiou, G. (1980), MNRAS, 193, 189
Ferrarese, L., & Merrit, D. 2000, ApJ, 539, L9
Firmani, C., & Tutukov, A.V. 1994, A&A, 288, 713
Firmani, C., Hernández, X. & Gallagher, J. 1996, A&A, 308, 403
Firmani, C., & Avila-Reese, V. 2000, MNRAS, 315, 457
Firmani, C., D'Onghia, E., Avila-Reese, V., Chincarini, G., & Hernández, X. 2000, MNRAS, 315, L29
Firmani, C., D'Onghia, E., Chincarini, G., Hernández, X., & Avila-Reese, V. 2001, MNRAS, 321, 713
Freeman, K.C. 1999, Astrophysics and Space Science, v. 269/270, p. 119
Gavazzi, G. 1993, ApJ, 419, 469
Gebhardt, K. et al. 2000, ApJ, 543, L5
Genzel, R., Tacconi, L.J., Rigopoulou, D., Lutz, D., & Tecza, M. 2001, ApJ, 563, 527
Giallongo, E., Menci, N., Poli, F., D'Odorico, S., & Fontana, A. 2000,ApJ, 530, L73
Giovanelli, R. et al. 1997, AJ, 113, 53
Gottlöber, S., Klypin, A., & Kravtsov, A.V. 2001, ApJ, 546, 223
Graham, A. W. & Colless, M. 1997, MNRAS, 287, 221
Graham, A. W., Erwin, P., Caon, N. & Trujillo, I. 2001, ApJ, 563, L11
Granato G.L. et al. 2001, MNRAS, 324, 757
Guzzo, L. 2002, in "Modern Cosmology", eds. S. Bonometto, V. Gorini & U. Moschella, Bristol, UK, 344
Hernández, X., Avila-Reese, V. & Firmani, C. 2001, MNRAS, 327, 329
Hernquist, L. 1990, ApJ, 356, 359
——— 1992, ApJ, 400, 460
——— 1993, ApJ, 409, 548
Hibbard, J.E., & Yun, M.S. 1999, ApJ, 522, L93
Hubble, E. 1936, The Realm of the Nebulae, (New Haven: Yale Univ. Press)
Jenkins, A. et al. 1998, ApJ, 499, 20
Kauffmann, G., White, S.D.M., & Guiderdoni, B. 1993, MNRAS, 264, 201
Kauffmann, G., Colberg, J.M., Diaferio, A., & White, S.D.M. 1999, MNRAS, 303, 188
Kauffmann, G., & Haehnelt, M. 2000, MNRAS, 311, 576
Kauffmann, G., Charlot, S., & Balogh, M.L. 2001, (astro-ph/0103130)
Kim, D.C., Veilleux, S., & Sanders, D.B. 2002, ApJS, 143, 277
Klypin, A.A., Kravtsov, A.V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Kormendy, J. 1977, ApJ, 218, 333
Krishna, G., & Biermann, P.L. 1998, å, 330, L37
Lacey, C.G., & Cole, S. 1993, MNRAS, 262, 627
Lemson, G. & Kauffmann, G. 1999, MNRAS, 302, 111
Lilly, S.J., Le Fevre, O., Hammer, F., & Crampton, D. 1996, ApJ, 460, L1
Lilly, S.J. et al. 1998, ApJ, 500, 75
Lilly, S.J. et al. 1999, The formation of galactic bulges, eds. C.M. Carollo, H.C. Ferguson, & R.F.G. Wyse, Cambridge, UK, 26
Magorrian, J. et al. 1998, AJ, 115, 2285
Makino, J., & Ebisuzaki, T. 1996, ApJ, 465, 527
Maller, A.H., Dekel, A., & Somerville, R. 2002, MNRAS, 329, 423
Mao, S., Mo, H.J., & White, S.D.M. 1998, MNRAS, 297, L71
Mathews, W.G. & Brighenti, F. 1999a, ApJ, 526, 114
——— 1999b, ApJ, 527, L31
Merrifield, M.R., & Kuijken, J. 1999, A&A, 345, L47
Merrifield, M.R., Forbes, D.A., & Terlevich, A. I. 2000, MNRAS, 313, L29
Meurer, G.R., Heckman, T., Lehnert, M., Leitherer, C., & Lowenthal, J. 1997, AJ, 114, 54
Mihos, J.C., & Hernquist, L. 1994, ApJ, 437, L47
——— 1996, ApJ, 464, 641
Milosavljevic, M., Merritt, D., Rest, A., & van den Bosch, F.C. 2002, MNRAS, 331, L51
Mo, H.J., Mao, S., White, S.D.M. 1998, MNRAS, 295,319
Mo, H.J., Mao, S. 2001, MNRAS, 318, 163
Moore, B. 1994, Nature, 370, 629
Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J. & Tozzi, P. 1999, ApJ, 524, L19
Murali, C., Katz, N., Hernquist, L., Weinberg, D.H., & Davé, R. 2002, ApJ, 571, 1
Naab, T., Burkert, A., & Hernquist, L. 1999, ApJ, 523, L133
Navarro, J.F., Frenk, C.S., & White, S.D.M. 1997, ApJ, 490, 493
Norman, C.A., Sellwood, J.A., & Hassan, H. 1996, ApJ, 462, 114
Nulsen, P.E.J., & Fabian A.C. 2000, MNRAS, 311, 346
Pahre, M.A. 1998, Ph. D. thesis, Caltech
Pahre, M.A., Djorgovski, S.G., & de Carvalho, R.R. 1998a, AJ, 116, 1591
——— 1998b, in ASP Conf. Series. 163, Star Formation in Early Type Galaxies, eds. P. Carral & J. Cepa, 17
Patton, D.R. et al. 2000, ApJ, 536, 153
Patton, D.R. et al. 2002, ApJ, 565, 208
Peebles, P.J.E. 1969, ApJ, 155, 393
———. 2003, in ASP Conf. Series 283, A New Era in Cosmology, eds. N. Metcalfe & T. Shanks, (astro-ph/0201015)
Pfenniger, D. 1996, Lecture Notes in Physics, 474, 91
Press, W.H., & Schechter, P. 1974, ApJ, 187, 425
Quinlan, G.D. 1997, New Astron., 1, 35
Quinlan, G.D., & Hernquist, L. 1997, New Astron., 2, 533
Renzini, A. 1994, in "Galaxy Formation", eds. J. Silk & N. Vittorio, (Elsevier Science Publishers B.V., The Netehrlands), p.303
Roberts, M.S. & Haynes, M.P. 1994, ARA&A, 32, 115
Roche, N., Ratnatunga, K., Griffiths, R.E., Im, M., & Naim, A. 1998, MNRAS, 293, 157
Salucci, P. 2001, MNRAS, 320, L1
Salucci, P., & Burkert, A. 2000, ApJ, 312, L27

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

Salvador-Sole, E., Solanes, J. M. & Manrique, A. 1998, ApJ, 499, 542
Sanders, D.B. & Mirabel, I.F. 1996, ARA&A, 34, 749
Sanders, D.B. 2001, IAU Colloquium 184, AGN Surveys, eds. R.F. Green, E.Y. Khachikian & D.B. Sanders, 29
Schweizer, F. 1982, ApJ, 252, 455
Shade, D.J., Boyle, B.J., & Letawsky, M. 2000, MNRAS, 315, 498
Silk, J., & Rees, M.J. 1998, A&A, 331, L1
Silk, J., & Wyse, R.F.G. 1993, Phys. Rep., 231, 295
Simard, L. et al. 1999, ApJ, 519, 563
Simien, F., & de Vaucouleurs, G. 1986, ApJ, 302, 564
Somerville, R.S., & Primack, J.R. 1999, MNRAS, 310, 1087
Somerville, R.S., & Kolatt, T.S. 1999, MNRAS, 305, 1
Steinmetz, M., & Navarro, J.F. 1999, ApJ, 513, 555
_____ 2002, NewA, 7, 155
Toft, S., Rasmussen, J., Sommer-Larsen, J. & Pedersen, K. 2002, MNRAS, 335, 799
Toomre, A., & Toomre, J. 1972, ApJ, 178, 623
Tóth, G., & Ostriker, J.P. 1992, ApJ, 389, 5
Treu, T., Stiavelli, M., Bertin, G., Casertano, S., & Moller, P. 2001, MNRAS, 326, 237
Tully, R.B., & Pierce, M.J. 2000, ApJ, 533, 744
Valenzuela, O. & Klypin, A. 2002, preprint (astro-ph/0204028)
van den Bergh, S. 2002, PASP, 114, 797
van den Bosch, F.C. 1998, ApJ, 507, 601
_____ 2000, ApJ, 530, 177
_____ 2001, MNRAS, 326, 1205
_____ 2002, MNRAS, 332, 456
van den Bosch, F.C., Abel, T., Croft, R.A.C., Hernquist, L., & White, S.D.M. 2002, ApJ, 576, 21
Veilleux, S., Kim, D.C. & Sanders, D.B. 2002, ApJS, 143, 315
Vitvitska, M. et al. 2002, ApJ, 581, 799
Vogt, N. et al. 1997, ApJ, 479, L121
Wechsler, R.H., Bullock, J.S., Primack, J.R., Kravtsov, A.V., & Dekel, A. 2002, ApJ, 568, 52
White, S.D.M., & Frenk, C.S. 1991, ApJ, 379, 52
White, S. D. M. & Rees, M. J. 1978, MNRAS, 183, 341
Wilman, R.J., Fabian, A.C., & Nulsen, P.E.J. 2000, MNRAS, 319, 583
Wyithe, J.S.B., & Loeb, A. 2002, ApJ, 581, 886
Wyse, R.F.G., Gilmore, G., & Franx, M. 1997, ARA&A, 35, 637

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
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