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The evolution of disc galaxies

The evolution of disc galaxies
BY SHAUN M. COLE¹, CARLTON BAUGH¹, CARLOS FRENK¹, N M. COLE¹, CARLTON BAUGH¹, CARLOS FRENK¹,
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We briefly describe the physical processes that are included in our semi-analytic
model of hierarchical galaxy formation. We review some of the low redshift prop-We briefly describe the physical processes that are included in our semi-analytic model of hierarchical galaxy formation. We review some of the low redshift properties of one such model constructed assuming a Λ CDM cosm We briefly describe the physical processes that are included in our semi-analytic model of hierarchical galaxy formation. We review some of the low redshift properties of one such model constructed assuming a Λ CDM cosm model of hierarchical galaxy formation. We review some of the low redshift properties of one such model constructed assuming a Λ CDM cosmology. We examine the evolutionary paths of typical bright disc galaxies in this m erties of one such model constructed assuming a ACDM cosmology. We examine
the evolutionary paths of typical bright disc galaxies in this model. This case study
serves to illustrate the generic features of galaxy evolution the evolutionary paths of typical bright disc galaxies in this model. This case study
serves to illustrate the generic features of galaxy evolution in hierarchical models. It
is demonstrated that the richness of galaxy evo serves to illustrate the generic features of galaxy evolution in hierarchical models. It
is demonstrated that the richness of galaxy evolution in this model is hidden when
one looks at the evolution of global properties su is demonstrated that the richness of galaxy evolution in this model is hidden when
one looks at the evolution of global properties such as the galaxy luminosity function.
We also quantify a generic prediction of hierarchic one looks at the evolution of global properties such as the galaxy luminosity function.
We also quantify a generic prediction of hierarchical galaxy formation, namely that
galaxies were physically smaller in the past. This We also quantify a generic prediction of hierarchical galaxy formation, namely that galaxies were physically smaller in the past. This model is consistent with recent high redshift observations and the reported evolution o galaxies were physically smaller in the past. This model is consistent with recent high redshift observations and the reported evolution of galaxy sizes lends general support to hierarchical galaxy formation.

Keywords: galaxies; formation; evolution

1. Introduction

Observations now probe the properties of galaxy populations over a large fraction of the Universe (e.g. Steidel *et al.* 1996; Ellis *et al.* 1996; Lilly *et al.* 1996; Lilly *et al.* 1996; Lilly *et al.* 1996; Lilly *et a* the age of the Universe (e.g. Steidel *et al.* 1996; Ellis *et al.* 1996; Lilly *et al.* 1996;
Adelberger *et al.* 1998). Furthermore, we can look forward to a much more detailed Observations now probe the properties of galaxy populations over a large fraction of
the age of the Universe (e.g. Steidel *et al.* 1996; Ellis *et al.* 1996; Lilly *et al.* 1996;
Adelberger *et al.* 1998). Furthermore, we the age of the Universe (e.g. Steidel *et al.* 1996; Ellis *et al.* 1996; Lilly *et al.* 1996; Adelberger *et al.* 1998). Furthermore, we can look forward to a much more detailed study of the high redshift Universe with t Adelberger *et al.* 1998). Furthermore, we can look forward to a much more detailed study of the high redshift Universe with the many instruments soon to be commissioned on the growing generation of new 8 m class telescop

study of the high redshift Universe with the many instruments soon to be commis-
sioned on the growing generation of new 8 m class telescopes. Over the lookback time
probed by these observations the conventional cold-darksioned on the growing generation of new 8 m class telescopes. Over the lookback time
probed by these observations the conventional cold-dark-matter-dominated models
of structure formation predict very strong evolution of t probed by these observations the conventional cold-dark-matter-dominated models
of structure formation predict very strong evolution of the distribution of dark mat-
ter. Thus the process of galaxy formation will be greatl In the distribution of dark matter. Thus the process of galaxy formation will be greatly influenced and probably \sum largely determined by the dynamical evolution of the dark matter. Frequences in the process of galaxy formation will be greatly influenced and probably early determined by the dynamical evolution of the dark matter.
Here we use the powerful technique of semi-analytic galaxy formation to

largely determined by the dynamical evolution of the dark matter.
Here we use the powerful technique of semi-analytic galaxy formation to investigate
galaxy evolution within the framework set by the hierarchical merging of Here we use the powerful technique of semi-analytic galaxy formation to investigate
galaxy evolution within the framework set by the hierarchical merging of dark matter
halos. A simpler but useful treatment of disc galaxy galaxy evolution within the framework set by the hierarchical merging of dark matter halos. A simpler but useful treatment of disc galaxy formation within the same framework, but ignoring the detailed merger histories of halos. A simpler but useful treatment of disc galaxy formation within the same
framework, but ignoring the detailed merger histories of the galaxies, is given by Mo
et al. (1998) and Mao *et al.* (1998). An even simpler framework, but ignoring the detailed merger histories of the galaxies, is given by Mo
et al. (1998) and Mao *et al.* (1998). An even simpler model for the disc evolution is
given by Dalcanton *et al.* (1997). In $\S 2$, *et al.* (1998) and Mao *et al.* (1998). An even simpler model for the disc evolution is given by Dalcanton *et al.* (1997). In $\S 2$, we briefly describe the physical processes that are included in the Cole *et al.* (200 given by Dalcanton *et al.* (1997). In \S 2, we briefly describe the physical processes that are included in the Cole *et al.* (2000) semi-analytic model of hierarchical galaxy formation. In \S 3, we specify a completely that are included in the Cole *et al.* (2000) semi-analytic model of hierarchical galaxy formation. In §3, we specify a completely determined Λ CDM model and compare its redshift zero properties with observations, a sub formation. In §3, we specify a completely determined Λ CDM model and compare
its redshift zero properties with observations, a subset of which have been used to
constrain the parameters of the model. This model is used its redshift zero properties with observations, a subset of which have been used to constrain the parameters of the model. This model is used as a case study to illustrate some of the generic features of hierarchical gala some of the generic features of hierarchical galaxy formation. In $\S 4$, we examine the
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2094 $S.$ *M. Cole and others*
evolutionary properties of this model and examine in detail the formation of several
randomly selected bright disc galaxies. We conclude in $\S 5$. evolutionary properties of this model and examine in detail trandomly selected bright disc galaxies. We conclude in $\S\,5$. randomly selected bright disc galaxies. We conclude in $\S 5$.
2. The model

A full description of the current Durham semi-analytic galaxy formation model, complete with an exploration of how the predictions depend on parameter variations and how they compare with observational data, can be found in Cole $et \ al.$ (2000). A full description of the current Durham semi-analytic galaxy formation model, complete with an exploration of how the predictions depend on parameter variations and how they compare with observational data, can be found i complete with an exploration of how the predictions depenand how they compare with observational data, can be for
Here we simply describe the main features of the model.

(*a*) *Merger trees*

 (a) *Merger trees*
We use a simple new Monte Carlo algorithm to generate merger trees that describe
e formation paths of randomly selected dark matter halos. Our algorithm is based We use a simple new Monte Carlo algorithm to generate merger trees that describe
the formation paths of randomly selected dark matter halos. Our algorithm is based
directly on the analytic expression for halo merger rates We use a simple new Monte Carlo algorithm to generate merger trees that describe
the formation paths of randomly selected dark matter halos. Our algorithm is based
directly on the analytic expression for halo merger rates the formation paths of randomly selected dark matter halos. Our algorithm is based
directly on the analytic expression for halo merger rates derived by Lacey $\&$ Cole
(1993). The algorithm enables the merger process to b directly on the analytic expression for halo merger rates derived by Lacey $\&$ Cole (1993). The algorithm enables the merger process to be followed with high time resolution, as time-steps are not imposed on the tree but $\frac{1}{\circ}$ by the frequency of mergers.

(*b*) *Halo structure and gas cooling*

We assume that the dark matter in virialized halos is well described by the NFW We assume that the dark matter in virialized halos is well described by the NFW
density profile (Navarro *et al.* 1997). We further assume that any diffuse gas present
during a halo merger is shock heated to the virial te We assume that the dark matter in virialized halos is well described by the NFW density profile (Navarro *et al.* 1997). We further assume that any diffuse gas present during a halo merger is shock heated to the virial te density profile (Navarro *et al.* 1997). We further assume that any diffuse gas present during a halo merger is shock heated to the virial temperature of the halo. The density profile we adopt for the hot gas is less cent during a halo merger is shock heated to the virial temperature of the halo. The density
profile we adopt for the hot gas is less centrally concentrated than that of the dark
matter and is chosen to be in agreement with th profile we adopt for the hot gas is less centrally concentrated than that of the dark
matter and is chosen to be in agreement with the results of high resolution simulations
of non-radiative gas (e.g. Frenk *et al.* 1999). matter and is chosen to be in agreement with the results of high resolution simulations
of non-radiative gas (e.g. Frenk *et al.* 1999). We estimate the fraction of gas that
can cool in a halo by computing the radius at w of non-radiative gas (e.g. Frenk *et al.* 1999). We estimate the fraction of gas that can cool in a halo by computing the radius at which the radiative cooling time of the gas equals the age of the halo. The gas that cool can cool in a halo by computing the radius at which the radiative cooling time of
the gas equals the age of the halo. The gas that cools is assumed to conserve angular
momentum and settle into a rotationally supported disc the gas equals the age of the halo. The gas that cools is assumed to conserve angular momentum and settle into a rotationally supported disc. Thus, the initial angular momentum of the halo, which we assign using the well-c momentum and settle into a rotationally supported disc. Thus, the initial angular
momentum of the halo, which we assign using the well-characterized distribution of
spin parameters found for halos in N-body simulations, de momentum of the halo, which we assign using the well-characterized distribution of spin parameters found for halos in N -body simulations, determines the size of the resulting galaxy disc. In computing the size of the di spin parameters found for halos in N -body simulations, determines the size
resulting galaxy disc. In computing the size of the disc we also take accoun
contraction of the inner part of the halo caused by the gravity of In tesulting galaxy disc. In computing the size of the disc we also take account of the contraction of the inner part of the halo caused by the gravity of the disc. In direct hydrodynamic simulations of galaxy formation (N

contraction of the inner part of the halo caused by the gravity of the disc.
In direct hydrodynamic simulations of galaxy formation (Navarro *et al.* 1995;
Navarro & Steinmetz 1999), the assumption that angular momentum i In direct hydrodynamic simulations of galaxy formation (Navarro *et al.* 1995; Navarro & Steinmetz 1999), the assumption that angular momentum is conserved during the assembly of a galaxy disc is broken. In these simulati Navarro & Steinmetz 1999), the assumption that angular momentum is conserved
during the assembly of a galaxy disc is broken. In these simulations, galaxies are
assembled by the merging of cold lumps, which are effective a during the assembly of a galaxy disc is broken. In these simulations, galaxies are
assembled by the merging of cold lumps, which are effective at transferring angu-
lar momentum to their common dark matter halo prior to me assembled by the merging of cold lumps, which are effective at transferring angular momentum to their common dark matter halo prior to merging. The resulting disc galaxies have smaller scale-lengths and lower specific angu \bigcirc lar momentum to their common dark matter halo prior to merging. The resulting disc galaxies have smaller scale-lengths and lower specific angular momenta than \bigcirc observed galaxy discs. As we shall see below, if i disc galaxies have smaller scale-lengths and lower specific angular momenta than observed galaxy discs. As we shall see below, if instead angular momentum conservation is assumed, the resulting disc scale-lengths match those observed quite well.
Thus, it seems likely that some process not currently inc vation is assumed, the resulting disc scale-lengths match those observed quite well.
Thus, it seems likely that some process not currently included in the direct simulations must be responsible for preventing efficient ang Thus, it seems likely that some process not currently included in the direct simulations must be responsible for preventing efficient angular momentum transport. The obvious candidate is stellar feedback which could suppre lations must be responsible for preventing efficient angular momentum transport.
The obvious candidate is stellar feedback which could suppress the formation of cold
sub-galactic lumps prior to the assembly of the final di The obvious candidate is stellar feedback which could suppress the formation of cold sub-galactic lumps prior to the assembly of the final disc and so reduce angular momentum transport. This is an important problem which m momentum transport. This is an important problem which merits further attention.
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(*c*) *Star formation and feedback*

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SCIENCES The processes of star formation and stellar feedback are the most uncertain to model. We adopt a flexible approach in which the star formation rate in the disc of cold gas is given by $\dot{M}_{\cdot} = M_{\text{col}}/\tau_{\cdot}$, with the ti The processes of star formation and stellar feedback are the most uncertamodel. We adopt a flexible approach in which the star formation rate in the cold gas is given by $\dot{M}_\star = M_{\text{cold}}/\tau_\star$, with the time-scale τ_\star p The processes of star formation and stellar feedback are the most uncertain to cold gas is given by $M_{\star} = M_{\text{cold}}/\tau_{\star}$, with the time-scale τ_{\star} parametrized as

$$
\tau_{\star} = \epsilon_{\star}^{-1} \tau_{\rm disc} (V_{\rm disc}/200 \text{ km s}^{-1})^{\alpha_{\star}}.
$$
\n(2.1)

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 $\tau_\star = \epsilon_\star^{-1} \tau_{\rm disc} (V_{\rm disc}/200~{\rm km~s^{-1}})^{\alpha_\star}. \eqno{(2)}$ We also adopt a feedback model in which for every solar mass of stars formed,

el in which for every solar mass of stars formed,
\n
$$
\beta = (V_{\rm disc}/V_{\rm hot})^{-\alpha_{\rm hot}}
$$
\n(2.2)

 $\beta = (V_{\text{disc}}/V_{\text{hot}})^{-\alpha_{\text{hot}}}$ (2.2)
solar masses are assumed to be reheated and ejected from the disc as a result of
energy input from young stars and supernovae. In these formulae, τ_{disc} and V_{disc} are solar masses are assumed to be reheated and ejected from the disc as a result of energy input from young stars and supernovae. In these formulae, τ_{disc} and V_{disc} are the dynamical time and circular velocity of th solar masses are assumed to be reheated and ejected from the disc as a result of energy input from young stars and supernovae. In these formulae, τ_{disc} and V_{disc} are the dynamical time and circular velocity of th energy input from young stars and supernovae. In these formulae, $\tau_{\rm disc}$ and $V_{\rm disc}$ are the dynamical time and circular velocity of the disc; ϵ_{\star} , α_{\star} , $\alpha_{\rm hot}$ and $V_{\rm hot}$ are the model parameters. These the dynamical time and circular velocity
model parameters. These parameters mu
galaxy properties in the local Universe. % galaxy properties in the local Universe.
(*d*) *Galaxy mergers*

Mergers between galaxies can occur, subsequent to the merger of their dark matter halos, if dynamical friction causes the orbits of the galaxies to decay. The result of a merger depends on the mass ratio of the merging galaxies. If they are comparable, halos, if dynamical friction causes the orbits of the galaxies to decay. The result of a
merger depends on the mass ratio of the merging galaxies. If they are comparable,
 $M_{\text{smaller}} > f_{\text{ellip}} M_{\text{larger}}$, then the merger is sa merger depends on the mass ratio of the merging galaxies. If they are comparable, $M_{\text{smaller}} > f_{\text{ellip}} M_{\text{larger}}$, then the merger is said to be violent and results in the formation of a spheroid. At this point, any cold gas $M_{\text{smaller}} > f_{\text{ellip}} M_{\text{larger}}$, then the merger is said to be violent and results in the formation of a spheroid. At this point, any cold gas present in the merger is assumed to undergo a burst of star formation, with a time formation of a spheroid. At this point, any cold gas present in the merger is assumed
to undergo a burst of star formation, with a time-scale equal to the dynamical time of
the forming spheroid and with feedback estimated to undergo a burst of star formation, with a time-scale equal to the dynamical time of
the forming spheroid and with feedback estimated using equation (2.2), but with the
circular velocity of the spheroid replacing that of the forming spheroid and with feedback estimated using equation (2.2) , but with the circular velocity of the spheroid replacing that of the disc. The size of the resulting spheroid is estimated assuming energy conservat circular velocity of the spheroid replacing that of the disc. The size of the resulting
spheroid is estimated assuming energy conservation in the merger (once dynamical
friction has eroded the orbits to the point where th spheroid is estimated assuming energy conservation in the merger (once dynamical
friction has eroded the orbits to the point where the galaxies interpenetrate) and
the virial theorem. For minor mergers, $M_{\text{smaller}} < f_{\text{ellip}}$ friction has eroded the orbits to the point where the galaxies interpenetrate) and
the virial theorem. For minor mergers, $M_{\text{smaller}} < f_{\text{ellip}} M_{\text{larger}}$, we simply assume
the cold gas is accreted by the disc and the stars by the virial theorem. For minor mergers, $M_{\text{smaller}} < f_{\text{ellip}} M_{\text{larger}}$, we simply assume
the cold gas is accreted by the disc and the stars by the bulge of the larger galaxy.
Taking $f_{\text{ellip}} = 0.3$ gives a relative frequency the cold gas is accreted by the disc
Taking $f_{\text{ellip}} = 0.3$ gives a relative
in accord with local observations. (*e*) *Stellar population synthesis and dust*

To convert the calculated star formation histories of each galaxy into observable luminosities and colours we use the stellar population synthesis model of Bruzual $\&$ Charlot (1993, 2000) together with the three-dimensional dust model of Ferrara *et al*. To convert the calculated star formation histories of each galaxy into observable
luminosities and colours we use the stellar population synthesis model of Ferrara *et al*.
(1999). For the former, we adopt the initial mass Charlot (1993, 2000) together with the three-dimensional dust model of Ferrara *et al.* (1999). For the former, we adopt the initial mass function of the solar neighbourhood as parametrized by Kennicutt (1983) and for the (1999). For the former, we adopt the initial mass function of the solar neighbourhood as parametrized by Kennicutt (1983) and for the latter we adopt their Milky Way extinction law and assume that the dust-to-gas ratio in metallicity.

3. Redshift zero properties

The response of this galaxy formation model to parameter changes has been explored extensively in Cole *et al.* (2000). They also present a reference model for a Λ CDM The response of this galaxy formation model to parameter changes has been explored extensively in Cole *et al.* (2000). They also present a reference model for a Λ CDM cosmology (with $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$ and $h = 0.$ extensively in Cole *et al.* (2000). They also present a reference model for a Λ CDM cosmology (with $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$ and $h = 0.7$), which reproduces many of the low redshift properties of the observed galaxy di redshift properties of the observed galaxy distribution. To illustrate the behaviour
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 κ -band luminosity functions of our $\Lambda{\rm CDM}$ movariety of observational estimates (symbols).

Figure 2. (a) This shows the *I*-band Tully–Fisher relation. The points are the observational data
of Mathewson *et al.* (1992). The solid line and error bars indicate the median and scatter in the
model. Here the circular of Mathewson et al. (1992). The solid line and error bars indicate the median and scatter in the model. Here the circular velocity that is plotted is that at the virial radius of the halo in which the galaxy formed. If instead one plots the circular velocity at half mass radius of the galaxy disc, the relation shifts to that indicated by the dashed line. (b) This shows real/redshift space correlation functions of the dark matter (thin solid/dashed) and galaxies (thick solid/dashed) and also observational esti correlation functions of the dark matter (thin solid/dashed) and galaxies (thick solid/dashed)

and also observational estimates of the real and redshift space galaxy correlation functions.

of hierarchical galaxy formation models we have chosen to explore the properties of

this fully specified ACDM model of hierarchical galaxy formation model.
this fully specified ACDM model.
In figures 1 and 2 we show a va this fully specified Λ CDM model.
In figures 1 and 2 we show a variety of the $z = 0$ properties of this model and

this fully specified Λ CDM model.
In figures 1 and 2 we show a variety of the $z = 0$ properties of this model and
compare them with observational data. The luminosity functions (figure 1) have been
used to constrain mos In figures 1 and 2 we show a variety of the $z = 0$ properties of this model and
compare them with observational data. The luminosity functions (figure 1) have been
used to constrain most of the galaxy formation model para compare them with observational data. The luminosity functions (figure 1) have been
used to constrain most of the galaxy formation model parameters. Additional param-
eters have been set by reference to slope of the Tully– used to constrain most of the galaxy formation model parameters. Additional parameters have been set by reference to slope of the Tully–Fisher relation (figure $2a$). The slope and scatter of this relation are reproduced

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Figure 3. The evolution of the B-band luminosity function, (a) for all galaxies and (b) for disc-dominated galaxies only. The data points show corresponding observational estimates at $z = 0$.

velocities are *ca*. 30% too large. (If one instead plots the circular velocities at the velocities are $ca.30\%$ too large. (If one instead plots the circular velocities at the virial radii of the halos in which the galaxies formed, these are typically 30% lower and result in a good match to the observed T velocities are $ca.30\%$ too large. (If one instead plots the circular velocities at the virial radii of the halos in which the galaxies formed, these are typically 30% lower and result in a good match to the observed T virial radii of the halos in which the galaxies formed, these are typically 30% lower
and result in a good match to the observed Tully–Fisher relation.) This problem
with the model seems to be related to the high central d and result in a good match to the observed Tully–Fisher relation.) This problem
with the model seems to be related to the high central densities of DM halos pro-
duced in cosmological CDM N-body simulations, as discussed with the model seems to be related to the high central
duced in cosmological CDM N-body simulations, as di
& Steinmetz (2000) and Steinmetz & Navarro (1999).
The real and redshift space galaxy correlation function ceed in cosmological CDM N-body simulations, as discussed recently by Navarro Steinmetz (2000) and Steinmetz & Navarro (1999).
The real and redshift space galaxy correlation functions shown in figure 2b were
t used to set

& Steinmetz (2000) and Steinmetz & Navarro (1999).
The real and redshift space galaxy correlation functions shown in figure 2b were
not used to set model parameters, and so may be regarded as model predictions. The real and redshift space galaxy correlation functions shown in figure 2b were
not used to set model parameters, and so may be regarded as model predictions.
They are in good agreement with observations. These clusterin not used to set model parameters, and so may be regarded as model predictions.
They are in good agreement with observations. These clustering properties of the
galaxy formation model were computed by combining the semi-an They are in good agreement with observations. These clustering properties of the galaxy formation model were computed by combining the semi-analytic model with cosmological N-body simulations, as described in Benson *et al* galaxy formation model were computed by combining the semi-analytic model with
cosmological N -body simulations, as described in Benson *et al.* (2000*a*). This paper
tests the robustness of these predictions to paramete cosmological N-body simulations, as described in Benson *et al.* (2000*a*). This paper
tests the robustness of these predictions to parameter variations and also explains
physically why on small scales a complex scale-dep tests the robustness of these predictions to parameter variations and also explains
physically why on small scales a complex scale-dependent bias arises between the
clustering of the galaxies and the dark matter. The depe physically why on small scales a complex scale-dependent bias arises between the clustering of the galaxies and the dark matter. The dependence of galaxy clustering in real and redshift space on galaxy properties (e.g. lum clustering of the galaxies and the dark matter. The dependence of galaxy clustering
in real and redshift space on galaxy properties (e.g. luminosity, morphology and
colour) is calculated and compared with observational dat in real and redshift space on galaxy properties (e.g. luminosity, morphology and colour) is calculated and compared with observational data in Benson *et al.* (2000*b*; see also Kauffmann *et al.* 1999*a*, *b*; Diaferio *e*

4. Evolution

(*a*) *Luminosity functions*

Figure 3 shows the prediction of our model for the evolution of the rest-frame ^B- band luminosity function both for the whole galaxy population and for a subsample of disc-dominated galaxies. We see that in both cases there is very little evolution of band luminosity function both for the whole galaxy population and for a subsample
of disc-dominated galaxies. We see that in both cases there is very little evolution of
the number density of L_{\star} galaxies out to at le of disc-dominated galaxies. We see that in both cases there is very little evolution of
the number density of L_{\star} galaxies out to at least redshift $z = 1$. This mild evolution,
which is similar to that seen observatio the number density of L_{\star} galaxies out to at least redshift $z = 1$. This mild evolution, which is similar to that seen observational samples (e.g. Brinchmann 1999), could be interpreted as indicating that disc galaxie interpreted as indicating that disc galaxies were largely in place at redshift $z = 1$ and *Phil. Trans. R. Soc. Lond.* A (2000)

o stellar mass
Figure 4. The formation histories of a random selection of present-day, bright, disc-dominated
galaxies. At a given redshift the number of shaded components equals the number of progenitors Figure 4. The formation histories of a random selection of present-day, bright, disc-dominated galaxies. At a given redshift the number of shaded components equals the number of progenitors and their widths indicate their galaxies. At a given redshift the number of shaded components equals the number of progenitors and their widths indicate their stellar masses.

national their widths indicate their stellar masses.

have simply gradually converted gas to stars over this time-span, at a fairly constant

star formation rate. As we shall see in the next section this interpretation is have simply gradually converted gas to stars over this time-span, at a fairly constant
star formation rate. As we shall see in the next section this interpretation is in stark
contrast with the actual evolution that occurs have simply gradually converted gas to stars over this time-spastar formation rate. As we shall see in the next section this intercontrast with the actual evolution that occurs in this model. (*b*) *Individual galaxies*

Figure 4 depicts the formation histories of a random sample of present-day, bright $(L > L_*)$, disc-dominated galaxies. (Here and below we use the term disc-dominated Figure 4 depicts the formation histories of a random sample of present-day, bright $(L > L_{\star})$, disc-dominated galaxies. (Here and below we use the term disc-dominated to denote galaxies with B-band bulge-to-total light rat $(L > L_*)$, disc-dominated galaxies. (Here and below we use the term disc-dominated to denote galaxies with *B*-band bulge-to-total light ratios less than 0.4.) We can see that the formation histories are very varied and to denote galaxies with *B*-band bulge-to-total l
that the formation histories are very varied are
progenitors of a wide range of stellar masses.
Some properties of this variety of formation at the formation histories are very varied and involve a number of mergers with
ogenitors of a wide range of stellar masses.
Some properties of this variety of formation paths are quantified in figure 5. Fig-
6. So shows t

progenitors of a wide range of stellar masses.
Some properties of this variety of formation paths are quantified in figure 5. Figure 5a shows the ratio of stellar disc mass today to that of the most massive disc
progenito Some properties of this variety of formation paths are quantified in figure 5. Figure 5a shows the ratio of stellar disc mass today to that of the most massive disc progenitor at redshift $z = 1$ as a function of the prese ure 5a shows the ratio of stellar disc mass today to that of the most massive disc
progenitor at redshift $z = 1$ as a function of the present-day disc luminosity. The
corresponding change in the rest-frame B-band magnitud

Figure 5. (a) The ratio of stellar disc mass today to that of the most-massive progenitor at redshift $z = 1$ as a function of the B-band magnitude of the present-day disc. (b) The corresponding change in B-band magnitude \bigcirc shift $z = 1$ as a function of the B-band magnitude of the present-day disc. (b) The corresponding \bigcirc change in B-band magnitude of the stellar disc.

Figure 6. Distributions of B-band bulge-to-total light ratios. (a) This is the distribution at $z = 1$ Figure 6. Distributions of *B*-band bulge-to-total light ratios. (a) This is the distribution at $z = 1$ for the largest progenitors of present-day bright, disc-dominated $(B/T < 0.4)$ galaxies. (b) This is the distribution a Figure 6. Distributions of *B*-band bulge-to-total light ratios. (*a*) This is the distribution at $z = 1$ for the largest progenitors of present-day bright, disc-dominated $(B/T < 0.4)$ galaxies. (*b*) This is the distributi

figure 5b. The mean disc mass has increased by a factor of 2 to 3 over this time-span
and this is accompanied by a modest increase in B-band luminosity of 0.0–0.5 mag figure 5b. The mean disc mass has increased by a factor of 2 to 3 over this time-span
and this is accompanied by a modest increase in B-band luminosity of $0.0-0.5$ mag.
However, the scatter about these mean trends is lar figure 5b. The mean disc mass has increased by a factor of 2 to 3 over this time-span
and this is accompanied by a modest increase in B-band luminosity of 0.0–0.5 mag.
However, the scatter about these mean trends is large and this is accompanied by a modest increase in *B*-band luminosity of 0.0–0.5 mag.
However, the scatter about these mean trends is large, with many discs growing by
more than factor 10 in mass and disc brightnesses varyi However, the scatter about these mean trends is large, with many discs growing by
more than factor 10 in mass and disc brightnesses varying by up to ± 2 mag. The
occurrence of some galaxies whose disc stellar mass decr more than factor 10 in mass and disc brightnesses varying by up to ± 2 mag. The occurrence of some galaxies whose disc stellar mass decreases from redshift $z = 1$ to $z = 0$ is a result of some discs being destroyed in occurrence of some galaxies whose disc stellar mass decreases from redshift $z = 1$ to $z = 0$ is a result of some discs being destroyed in major mergers and later being renewed by the subsequent accretion of cooling gas.

The luminosity changes quantified above are large compared with the modest renewed by the subsequent accretion of cooling gas.
The luminosity changes quantified above are large compared with the modest
change in the characteristic luminosity, L_{\star} , during this same time-interval shown
in figu The luminosity changes quantified above are large compared with the modest
change in the characteristic luminosity, L_{\star} , during this same time-interval shown
in figure 3. This implies that there can be no simple one-t change in the characteristic luminosity, L_{\star} , during this same time-interval shown
in figure 3. This implies that there can be no simple one-to-one correspondence
between the brightest galaxies at redshift $z = 1$ and in figure 3. This implies that there can be no simple one-to-one correspondence
between the brightest galaxies at redshift $z = 1$ and those today. One example of
this is illustrated in figure 6, which depicts the distribu between the brightest galaxies at redshift $z = 1$ and those today. One example of
this is illustrated in figure 6, which depicts the distribution of B-band bulge-to-total
luminosity ratios for bright, disc-dominated galax this is illustrated in figure 6, which depicts the distribution of *B*-band bulge-to-total luminosity ratios for bright, disc-dominated galaxies selected at $(a) z = 0$ and $(b) z = 1$. From this we see that even the morphologi $z = 1$. From this we see that even the morphological classification of these galaxies *Phil. Trans. R. Soc. Lond.* A (2000)

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stellar mass
Figure 7. As figure 4, but for progenitors (indicated by the asterisks) that are selected to be
pright disc-dominated galaxies at redshift $z = 1$. The bulge-to-total ratios of the descendant at Figure 7. As figure 4, but for progenitors (indicated by the asterisks) that are selected to be bright disc-dominated galaxies at redshift $z = 1$. The bulge-to-total ratios of the descendant at $z = 0$, both by B-band ligh

 $z = 0$, both by *B*-band light and mass, are indicated above each panel.
can vary significantly between the two epochs. In particular, a significant fraction of can vary significantly between the two epochs. In particular, a significant fraction of
the bright disc galaxies at redshift $z = 1$ are destined to become elliptical galaxies
at the present day can vary significantly
the bright disc galax
at the present day.
Given these gross e bright disc galaxies at redshift $z = 1$ are destined to become elliptical galaxies
the present day.
Given these gross changes it is clear that the merger and star formation histories
picted in figure 5, while being typi

at the present day.
Given these gross changes it is clear that the merger and star formation histories
depicted in figure 5, while being typical for disc galaxies selected at redshift $z = 0$,
will not be representative of Given these gross changes it is clear that the merger and star formation histories depicted in figure 5, while being typical for disc galaxies selected at redshift $z = 0$, will not be representative of the fate of disc ga depicted in figure 5, while being typical for disc galaxies selected at redshift $z = 0$, will not be representative of the fate of disc galaxies selected at an earlier time. This is illustrated in figure 7, which shows th will not be representative of the fate of disc galaxies selected at an earlier time. This
is illustrated in figure 7, which shows the star formation and merger histories of a
random sample of $z = 1$, bright $(L > L_*)$ disc-d is illustrated in figure 7, which shows the star formation and merger histories of a
random sample of $z = 1$, bright $(L > L_{\star})$ disc-dominated galaxies. Many of the
bright disc galaxies at redshift $z = 1$ are destined to u random sample of $z = 1$, bright $(L > L_*)$ disc-dominated galaxies. Many of the bright disc galaxies at redshift $z = 1$ are destined to undergo quite strong mergers before the present.
Figure 8 is analogous to figure 6, but bright disc galaxies at redshift $z = 1$ are destined to undergo quite strong mergers

at redshift $z = 1$ rather than at $z = 0$. Here, we use different symbols to indicate the

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Figure 8. The change in mass and magnitude between redshifts $z = 1$ and $z = 0$ of the discs of galaxies selected as bright and disc-dominated at $z = 1$. (a) The ratio of stellar disc masses as a function of the *R*-band m galaxies selected as bright and disc-dominated at $z = 1$. (a) The ratio of stellar disc masses as a function of the B-band magnitude of the $z = 1$ disc. (b) The corresponding change in B-band magnitude of the stellar disc $z = 0$ are spirals (disc-dominated) and filled triangles for galaxies whose descendants are $E/S0$ galaxies.

morphology of the galaxy at redshift $z = 0$. Figure 8a shows the ratio of the stellar morphology of the galaxy at redshift $z = 0$. Figure 8*a* shows the ratio of the stellar disc mass of the descendant at $z = 0$ to that of the largest progenitor disc at redshift $z = 1$. The corresponding change in the rest morphology of the galaxy at redshift $z = 0$. Figure 8a shows the ratio of the stellar disc mass of the descendant at $z = 0$ to that of the largest progenitor disc at redshift $z = 1$. The corresponding change in the rest-f $z = 1$. The corresponding change in the rest-frame *B*-band magnitude of the disc
is shown in figure 8b. As in figure 6a we see that the mean disc mass has increased
by a factor of 2 to 3 over this time-span, but now ther is shown in figure 8b. As in figure $6a$ we see that the mean disc mass has increased is shown in figure 8b. As in figure 6a we see that the mean disc mass has increased
by a factor of 2 to 3 over this time-span, but now there is an additional population
of discs whose masses have decreased dramatically du by a factor of 2 to 3 over this time-span, but now there is an additional population
of discs whose masses have decreased dramatically due to mergers that result in
bulge-dominated galaxies at the present day. In figure 8 of discs whose masses have decreased dramatically due to mergers that result in
bulge-dominated galaxies at the present day. In figure 8b we see that the typical disc
luminosity of this sample is 1-1.5 mag brighter at $z =$ bulge-dominated galaxies at the present day. In figure 8b we see that the typical disc
luminosity of this sample is 1–1.5 mag brighter at $z = 1$ than at $z = 0$. The sign of
this evolution is opposite to that for the sampl this evolution is opposite to that for the sample selected at redshift $z = 0$. This can
be understood in terms of the varied and non-monotonic evolution of the individual this evolution is opposite to that for the sample selected at redshift $z = 0$. This can
be understood in terms of the varied and non-monotonic evolution of the individual
galaxy luminosities together with the fact that we be understood in terms of the varied and non-monotonic evolution of the individual galaxy luminosities together with the fact that we have selected the brightest objects at one or other epoch. Thus, the galaxies will tend at one or other epoch. Thus, the galaxies will tend to be brightest at the epoch at which they are selected.

5. Observational tests (*a*) *Deep counts*

 (a) Deep counts
In the previous section we have seen that in a hierarchical model, galaxy evolution is
a complex process involving mergers and morphological transformations of galaxies In the previous section we have seen that in a hierarchical model, galaxy evolution is
a complex process involving mergers and morphological transformations of galaxies,
as well as non-monotonic evolution of their luminos In the previous section we have seen that in a hierarchical model, galaxy evolution is
a complex process involving mergers and morphological transformations of galaxies,
as well as non-monotonic evolution of their luminosi a complex process involving mergers and morphological transformations of galaxies, as well as non-monotonic evolution of their luminosities. In figure 9 we show that despite this complexity, its predictions are in good agr as well as non-monotonic evolution of their luminosities. In figure 9 we show that
despite this complexity, its predictions are in good agreement with the evolution of
the observed galaxy population when quantified in ter despite this complexity, its predictions are in good agreement with the evolution of
the observed galaxy population when quantified in terms of morphologically classified
galaxy counts. This figure is similar to that in Ba the observed galaxy population when quantified in terms of morphologically classified galaxy counts. This figure is similar to that in Baugh *et al.* (1996), but the model curves are for the newer ACDM model of Cole *et al* galaxy counts. This figure is similar to that in Baugh *et al.* (1996), but the model curves are for the newer Λ CDM model of Cole *et al.* (2000). It is noteworthy that this hierarchical model naturally reproduces both curves are for the newer Λ CDM model of Cole *et al.* (2000). It is noteworthy that this hierarchical model naturally reproduces both the total observed counts and the trend for the Irregular/Merger class to become an i this hierarchical mod
trend for the Irregula
fainter magnitudes. *Phil. Trans. R. Soc. Lond.* A (2000)

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Figure 9. The total and morphologically split *I*-band counts compared with various observational
estimates (symbols). In the model, spirals are defined (in the *I*-band) to have 0.05 $\lt B/T \lt 0.4$ Figure 9. The total and morphologically split *I*-band counts compared with various observational estimates (symbols). In the model, spirals are defined (in the *I*-band) to have $0.05 < B/T < 0.4$, E/S0 have $B/T > 0.4$ and Ir estimates (symbols). In the model, spirals are defined (in the I-band) to have $0.05 < B/T < 0.4$, $E/S0$ have $B/T > 0.4$ and Irregular/Peculiars have either $B/T < 0.05$ or have experienced a merger induced burst of star formation the last 1 Gyr. The contribution of this last category to the counts is shown by the dashed merger induced burst of star formation the last 1 Gyr. The contribution of this last category to

(*b*) *The stellar mass function*

In the model the relation between mass and luminosity is complicated and time-In the model the relation between mass and luminosity is complicated and time-
varying. Thus, much of the ambiguity in the nature of the galaxy evolution could
be removed if one could study the stellar mass rather than th In the model the relation between mass and luminosity is complicated and time-
varying. Thus, much of the ambiguity in the nature of the galaxy evolution could
be removed if one could study the stellar mass rather than the varying. Thus, much of the ambiguity in the nature of the galaxy evolution could
be removed if one could study the stellar mass rather than the luminosity. This is
becoming possible using deep redshift surveys with infrare be removed if one could study the stellar mass rather than the luminosity. This is
becoming possible using deep redshift surveys with infrared colours so that evolu-
tionary and k-corrections can be estimated and stellar becoming possible using deep redshift surveys with infrared colours so that evolutionary and k -corrections can be estimated and stellar masses inferred. Figure 10 shows the evolution of the stellar mass function for the *Phil. Trans. R. Soc. Lond.* A (2000)

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evolution of the stellar mass function (a) for disc-dominated galaxies only.

and (b) for disc-dominated galaxies only.
for a subsample of disc-dominated galaxies. In both cases there is a steady monotonic
evolution of the characteristic galaxy stellar mass. for a subsample of disc-dominated galaxies. In both c evolution of the characteristic galaxy stellar mass. evolution of the characteristic galaxy stellar mass.
(*c*) *Disc scale-lengths*

(c) $Disc\ scale-lengths$
A prediction that is at the very heart of hierarchical galaxy formation is that
laxies were physically smaller in the past. This is quantified for our $ACDM$ model A prediction that is at the very heart of hierarchical galaxy formation is that galaxies were physically smaller in the past. This is quantified for our Λ CDM model by the evolving distributions of disc scale-lengths sh A prediction that is at the very heart of hierarchical galaxy form galaxies were physically smaller in the past. This is quantified for our λ by the evolving distributions of disc scale-lengths shown in figure 11. Sinc shown in figure 11. Since the predicted distributions of disc scale-lengths shown in figure 11. Since the predicted distributions are broad and dependent on luminosity as well redshift, one has to be careful to match sele

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VCES** by the evolving distributions of disc scale-lengths shown in figure 11.
Since the predicted distributions are broad and dependent on luminosity as well
as redshift, one has to be careful to match selection criteria when co Since the predicted distributions are broad and dependent on luminosity as well
as redshift, one has to be careful to match selection criteria when comparing with
observational results. This has been done in figure 12, wh as redshift, one has to be careful to match selection criteria when comparing with
observational results. This has been done in figure 12, which shows the model distri-
bution of the scaled disc scale-length $C_R \equiv R_{\text{disc}}/$ observational results. This has been done in figure 12, which shows the model distribution of the scaled disc scale-length $C_R \equiv R_{\text{disc}}/M_{\text{lum}}^{1/3}$ as a function of redshift for a sample chosen to match the observation bution of the scaled disc scale-length $C_R = R_{\text{disc}}/M_{\text{lum}}^{1/3}$ as a function of redshift for
a sample chosen to match the observational sample analysed by Brinchmann (1999).
The line on the plot is a fit to the observe

a sample chosen to match the observational sample analysed by Brinchmann (1999). The line on the plot is a fit to the observed data and indicates that the evolution detected in the scale-length distribution is broadly cons The line on the plot is a fit to the observed data and indicates that the evolution

6. Conclusions

We have illustrated some of the generic features of galaxy evolution in a hierarchical model. In such models, galaxy formation is a recent process with approximately half We have illustrated some of the generic features of galaxy evolution in a hierarchical
model. In such models, galaxy formation is a recent process with approximately half
the stars forming since redshift $z = 1.0{\text -}1.5$. model. In such models, galaxy formation is a recent process with approximately half
the stars forming since redshift $z = 1.0{\text -}1.5$. The expected evolution of individual
disc galaxies is complex and often involves substa disc galaxies is complex and often involves substantial accretion and mergers. This results in there not being a one-to-one correspondence between bright galaxies at disc galaxies is complex and often involves substantial accretion and mergers. This
results in there not being a one-to-one correspondence between bright galaxies at
redshifts $z = 1$ and $z = 0$. The events in this complex results in there not being a one-to-one correspondence between bright galaxies at redshifts $z = 1$ and $z = 0$. The events in this complex formation history are not evident in studies of global properties such as the evolu redshifts $z = 1$ and $z = 0$. The events in this complex formation history are not evident in studies of global properties such as the evolution of galaxy luminosity functions or number counts. In particular, the luminosit evident in studies of global properties such as the evolution of galaxy luminosity functions or number counts. In particular, the luminosity function evolves very little from $z = 1$ to $z = 0$. In this case, if one were to

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Figure 11. For different I -band absolute magnitudes the curves show the evolution of the distribution of disc scale-lengths. The data points show the observed distributions at $z = 0$ as Figure 11. For different *I*-band absolute magnitudes the curves show the evolution of the distribution of disc scale-lengths. The data points show the observed distributions at $z = 0$ as estimated by De Jong & Lacey (200 tribution of disc scale-lengths. The datestimated by De Jong & Lacey (2000). The very large/small scale-length galaxies.

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Figure 12. The points show the evolution of the scaled disc size, $C_R \equiv R_{\text{disc}}/M_{\text{stars}}^{1/3}$, with redshift
for a sample of galaxies with 17.0 < I_{AB} < 22.5 and $R_{\text{disc}} > 2b^{-1}$ kpc. The straight line is the Figure 12. The points show the evolution of the scaled disc size, $C_R \equiv$ for a sample of galaxies with $17.0 < I_{AB} < 22.5$ and $R_{disc} > 2h^{-1}$ k fit found by Brinchmann (1999) for a similarly selected observation: for a sample of galaxies with $17.0 < I_{AB} < 22.5$ and $R_{\text{disc}} > 2h^{-1}$ kpc. The straight line is the Figure 12. The points show the evolution of the scaled disc size, $C_R \equiv R_{\text{disc}}/M_{\text{sta}}^{2+}$ for a sample of galaxies with $17.0 < I_{AB} < 22.5$ and $R_{\text{disc}} > 2h^{-1}$ kpc. The str fit found by Brinchmann (1999) for a similarly

fit found by Brinchmann (1999) for a similarly selected observational sample.
between the bright galaxies, as is done in the traditional pure luminosity evolution
models (e.g. Campos & Shanks 1997), one would falsely infe between the bright galaxies, as is done in the traditional pure luminosity evolution
models (e.g. Campos & Shanks 1997), one would falsely infer that present-day disc between the bright galaxies, as is done in the traditional pure luminosity evolution
models (e.g. Campos & Shanks 1997), one would falsely infer that present-day disc
galaxies have varied very little in luminosity since models (e.g. Campos & Shanks 1997), one would falsely infer that present-day disc
galaxies have varied very little in luminosity since $z = 1$. The generic prediction of
hierarchical galaxy formation, that the disc scale-l galaxies have varied very little in luminosity since $z = 1$. The generic pre
hierarchical galaxy formation, that the disc scale-lengths should be smalle
redshift, has been detected and is at the level predicted by such mo

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