1.65 MICRON (H BAND) SURFACE PHOTOMETRY OF GALAXIES. VI. THE HISTORY OF STAR FORMATION IN NORMAL LATE-TYPE GALAXIES

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ABSTRACT

We have collected a large body of near-IR (H band), UV (2000 Å), and Hα measurements of late-type galaxies. These are used jointly with spectral evolution models to study the initial mass function (IMF) in the mass range \( m > 2 M_\odot \). For spirals (Sa–Sd), Magellanic irregulars (Im), and blue compact dwarfs, our determination is consistent with a Salpeter IMF with an upper mass cutoff \( M_{\text{up}} \sim 80 M_\odot \). The history of star formation and the amount of total gas (per unit mass) of galaxies are found to depend primarily on their total masses (as traced by the H-band luminosities) and, only secondarily, on morphological type. The present star formation activity of massive spirals is up to 100 times smaller than that averaged over their lifetime, while in low-mass galaxies it is comparable to or higher than that at earlier epochs. Dwarf galaxies presently have larger gas reservoirs per unit mass than massive spirals. The efficiency in transforming gas into stars and the timescale for gas depletion (\( \sim 10 \text{ Gyr} \)) are independent of the luminosity and morphological type. This evidence is consistent with the idea that galaxies are coeval systems, that they evolved as closed boxes, forming stars following a simple, universal star formation law whose characteristic timescale is small (\( \tau \sim 1 \text{ Gyr} \)) in massive spirals and large (\( \tau > 10 \text{ Gyr} \)) in low-mass galaxies. A similar conclusion was drawn by Gavazzi & Scodeglio in 1996 to explain the color-magnitude relation of late-type galaxies. The consequences of this interpretation on the evolution of the star formation rate and the gas density per comoving volume of the universe with look-back time are discussed.

Key words: galaxies: evolution — galaxies: general — galaxies: ISM — galaxies: spiral — stars: formation — ultraviolet emission

1. INTRODUCTION

The hierarchical (Cole et al. 1994) and monolithic collapse (Sandage 1986) scenarios of galaxy formation make different predictions about the evolution of the primeval density perturbations that gave birth to galaxies. While in hierarchical models small objects form first and large objects are formed via successive merging of smaller structures, in the monolithic scenario galaxies are formed via a unique collapse of the original density perturbation without any interaction with the environment (closed box). A wide variety of physical and morphological properties observed in nearby galaxies are expected from both models: while in a monolithic scenario elliptical galaxies should have formed most of their stars in a short time compared with the collapse time, in order to avoid the formation of a disk by gas-gas dissipation, in spirals the slower initial star formation activity allows a significant fraction of gas to form a rotating disk (Sandage 1986). In hierarchical models, the different properties of galaxies are the result of the initial conditions of the original merger.

The predicted luminosity functions and density distributions of galaxies in the universe should, in principle, allow us to observationally disentangle these two models (Kauffmann et al. 1999). Furthermore, these models make predictions about the time evolution of the physical properties of galaxies, such as their structural parameters (e.g., bulge-to-disk ratio), dynamics, star formation history (and thus their stellar populations), gaseous content, and metal enrichment (Kauffmann & Charlot 1998 and references therein). An accurate determination of the dependence of these properties on redshift \( z \) (see, e.g., Cowie et al. 1996) will allow us to discriminate between the galaxy formation scenarios.

A detailed knowledge of the phenomenology of galaxies at \( z = 0 \), which represents the present stage of galaxy evolution, is of primary importance for constraining evolutionary models. Ironically, the zero point of galaxy evolution is still not sufficiently well determined, because of the lack of extensive observations of local galaxies. For example, the systematics of their current star formation activity, gaseous content, and metallicity are still poorly known. In particular, the UV and Hα observations, which are representative of the current star formation activity of galaxies (Donas et al. 1987; Kennicutt 1998), the near-IR data, which trace the old stellar population, and spectrophotometric measurements (Zaritsky, Kennicutt, & Huchra 1994), which are necessary to derive the properties of the underlying stellar population and the physical conditions of the interstellar medium, are still rare.

With the ambitious aim of constructing a representative
description of the physical properties of nearby galaxies, we undertook a multifrequency survey of \( \sim 3500 \) optically selected galaxies spanning the broadest possible range of morphological type (elliptical, spiral, dE, Im, and blue compact dwarf), luminosity \((-22 \leq M_B \leq -13\) and environmental conditions (clusters and isolated). Our own Hz, near-IR, millimeter, and centimeter observations, together with data from the literature, were collected in a multifrequency database (see Gavazzi, Pierini, & Boselli 1996b).

This database has been used to interpret the color-magnitude relation (Gavazzi & Scodeggio 1996) and star formation activity (Gavazzi et al. 1998) of late-type galaxies. The extension of our near-IR survey to faint spirals, Im galaxies, and blue compact dwarfs (BCDs), which is the subject of the present series of papers, combined with recent H\(\alpha\) observations of a set of late-type galaxies and the large body of available H \(\alpha\) and CO radio data, make it possible to study, in the present work, the phenomenology of the young stellar population and of the gas content of a large sample of late-type galaxies from Sa to Im and BCD.

Previous works devoted to analyzing the phenomenology of nearby galaxies have shown that the fraction of available gas and the activity of star formation (normalized to the visible stellar luminosity) increases along the Hubble sequence (Roberts & Haynes 1994; Kennicutt 1998). However, none of these works focused on the role of the total mass in governing the evolution of galaxies, an issue that we address in the present work. We do so using the observation that the near-IR H\(\alpha\) luminosity, which is dominated by the emission of old main-sequence and red giant stars (Bruzual & Charlot 1993), is a direct tracer of the dynamical mass of late-type systems (within the optical radius; Gavazzi et al. 1996b). Since the near-IR mass-to-light ratio was found not to vary with mass for galaxies spanning the entire range in morphological type from Sa to Im and BCD, contrary to what was found in the optical, by normalizing other observed quantities (e.g., the gas content) to the near-IR luminosity we are able to remove the well-known observed luminosity-luminosity or luminosity-mass scaling relation better than we could using optical luminosities. Furthermore, the decomposition of the near-IR light profiles is used to discriminate between disk-dominated and bulge-dominated galaxies. This new approach is made possible by the availability of a large body of near-IR observations of nearby galaxies, as described in Papers I–IV of this series. Furthermore, the available H \(\alpha\) and CO data allow a precise determination of the total gas content for a sample of galaxies with broad coverage in morphological type and luminosity.

The sample used and the data covered are described in § 2. Early-type \((>\text{Sa})\) galaxies are excluded from the present analysis since their UV emission, being dominated by the extreme horizontal-branch stars and their progenitors (Dorman, O’Connell, & Rood 1995), does not give information on the young stellar population. Moreover, we restrict the present analysis to galaxies that do not show signs of interaction with their surroundings. For this we use the H \(\alpha\) deficiency parameter to discriminate between “normal” galaxies and galaxies suffering from gas depletion because of ram pressure, and we include in the present study only isolated objects and cluster galaxies with an H \(\alpha\) deficiency (defined as the ratio of the H \(\alpha\) mass to the average H \(\alpha\) mass of isolated objects of similar morphological type and linear size; Haynes & Giovanelli 1984) of \(\leq 0.3\).

The current star formation rate (SFR) and the initial mass function (IMF) of late-type galaxies are studied in § 3. The dependence of the total (atomic plus molecular) gas content as a function of morphological type and luminosity is analyzed in § 4. A model for the star formation history of late-type galaxies is presented in § 5. The dependence of the SFR and gas density of the universe on look-back time is briefly discussed in § 6. An appendix describes how the Hz and UV (2000 Å) data are corrected for [N \(\alpha\)] contamination and internal extinction.

2. THE SAMPLE

Galaxies analyzed in this work are taken from the Zwicky catalog (CGCG; Zwicky et al. 1961–1968) \((m_{pg} \leq 15.7)\). They are either late-type \((>\text{Sa})\) members of three nearby \((\leq 8000 \text{ km s}^{-1})\) clusters (Cancer, A1367, Coma) or located in the relatively low density regions of the Coma-A1367 supercluster \((11^\circ 30^\prime < \text{R.A.} < 13^\circ 30^\prime; 18^\circ < \text{decl.} < 32^\circ)\), as defined in Gavazzi, Carrasco, & Galli (1999b). To extend the present study to lower luminosities, we include in the sample the late-type Virgo Cluster galaxies brighter than \(m_{pg} \leq 14.0\) listed in the Virgo Cluster Catalog (VCC; Binggeli, Sandage, & Tammann 1985) as cluster members. Furthermore, VCC galaxies with \(14.0 \leq m_{pg} \leq 16.0\) included in the “ISO” subsample described in Boselli et al. (1997b), observed as part of the central program with the Infrared Space Observatory, and CGCG galaxies in the region \(12^\circ < \text{R.A.} < 13^\circ, 0^\circ < \text{decl.} < 18^\circ\) but outside the VCC are considered. To avoid systematic environmental effects, we consider the subsample of late-type galaxies whose H \(\alpha\) deficiency is \(\leq 0.3\), typical of unperturbed, isolated galaxies. The final combined sample comprises 233, mainly “normal” galaxies (a few starburst or active galaxies might however be included).

The accuracy of the morphological classification is excellent for the Virgo galaxies (Binggeli et al. 1985; Binggeli, Popescu, & Tammann 1993). Because of the higher distance, the morphology of galaxies belonging to the other surveyed regions suffers from an uncertainty of about 1.5 Hubble type bins. We assume a distance of 17 Mpc for the members (and possible members) of Virgo Cluster A, 22 Mpc for Virgo Cluster B, and 32 Mpc for objects in the M and W clouds (see Gavazzi et al. 1999a). Members of the Cancer, Coma, and A1367 clusters are assumed to lie at distances of 62.6, 86.6, and 92 Mpc, respectively. Isolated galaxies in the Coma supercluster are assumed to lie at their redshift distance, adopting \(H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}\). For the 233 optically selected galaxies, complementary data are available in other bands as follows: 100% have H \(\alpha\) \((1420 \text{ MHz})\) and 99% have H-band \((1.65 \mu \text{m})\) data available. Much sparser coverage exists in the UV (2000 Å; 29%), CO \((115 \text{ GHz}; 38%)\), and Hz \((6563 \text{ Å}; 65%)\), as shown in Tables 1 and 2. The morphological distribution of galaxies is given in Table 3.

2.1. Data Analysis

Hz + [N \(\alpha\)] fluxes obtained from imaging, aperture photometry, or integrated spectra are taken from Kennicutt & Kent (1983), Kennicutt, Bothun, & Schommer (1984), Gavazzi, Boselli, & Kennicutt (1991), Gavazzi et al. (1998), Young et al. (1996), Almoznino & Brosch (1998), Moss, Whittle, & Pesce (1998), Heller, Almoznino, & Brosch (1999), and references therein. Hz fluxes from Kennicutt & Kent (1983), Kennicutt et al. (1984), and Gavazzi et al. (1991) have been multiplied by 1.16, as suggested by Ken-
nicutt, Tamblyn, & Congdon (1994), in order to account for the continuum flux overestimate due to the inclusion of the telluric absorption band near 6900 Å in the comparison filter. Additional observations of 66 galaxies have been obtained recently by us during several runs at the Observatoire de Haute Provence (France), at San Pedro Mártir (Mexico), and at Calar Alto (Boselli et al. 2001; Gavazzi et al. 2001). The estimated error on the Hα + [N II] flux is ~15%.

The UV data (at 2000 Å) are taken from the FOCA (Milliard, Donas, & Laget 1991) and FAUST (Lampton, Deharveng, & Bowyer 1990) experiments; UV magnitudes are from Deharveng et al. (1994), Donas et al. (1987, 1990, 2001), and Donas, Milliard, & Laget (1995). The estimated error on the UV magnitude is 0.3 mag in general, but it ranges from 0.2 mag for bright galaxies to 0.5 mag for weak sources observed in frames with larger than average calibration uncertainties.

The H I data are taken from Scodeggio & Gavazzi (1993) and Hoffman et al. (1996 and references therein). H I fluxes are transformed into neutral hydrogen masses with an uncertainty of ~10%.

CO data, used to estimate the molecular hydrogen content, are from Boselli et al. (1997a), Boselli, Casoli, & Lequeux (1995), and references therein. The average error on CO fluxes is ~20%; the error on the H2 content, however, is significantly larger (and difficult to quantify) because of the poorly known CO-to-H2 conversion factor (see Boselli et al. 1997a).

Near-IR data, mostly from NICMOS3 observations, are taken from this series of papers: Gavazzi et al. (1996a, 1996c, hereafter Papers I and II, respectively), Boselli et al. (1997b), Gavazzi et al. (2000a, hereafter Paper III), and Boselli et al. (2000, hereafter Paper IV). From these data, we derive total (extrapolated to infinity) magnitudes H_T determined as described in Gavazzi et al. (2000b, hereafter Paper V) with typical uncertainties of ~10%. These are converted into total luminosities using log L_H = 11.36 - 0.4 H_T + 2 log D (in solar units), where D is the distance to the source (in Mpc). For a few objects, we derive the H luminosity from K-band measurements assuming an average H - K color of 0.25 mag (independent of type; see Paper III).

A minority of the objects in our sample have an H-band magnitude obtained from aperture photometry, thus having no asymptotic extrapolation. For these, we use the magnitude H_25 determined as in Gavazzi & Boselli (1996) at the optical radius (the radius at which the B surface brightness is 25 mag arcsec$^{-2}$), which is on average 0.1 mag fainter than H_T (Gavazzi et al. 2000a, 2000b).

The total H magnitudes are corrected for internal extinction according to Gavazzi & Boselli (1996). No correction has been applied to galaxies of types later than Sed. The model-independent near-IR concentration index parameter C_{31}, defined as the ratio of the radii containing 75% to 25% of the total light of a galaxy, will be used throughout the paper to discriminate between disk-dominated and bulge-dominated galaxies. As shown in Paper V, pure exponential disks are characterized by C_{31} < 3, while C_{31} > 3 in galaxies with prominent bulges.

3. STAR FORMATION RATE IN GALAXIES

Various indicators of the star formation activity of late-type galaxies have been proposed in the literature (see Kennicutt 1998 for a review). In the present analysis we use the Hα and UV (2000 Å) luminosities, which are commonly accepted as the most direct indicators of the SFR.

3.1. SFR from Hα and UV (2000 Å) Luminosities

The Hα luminosity gives a direct measure of the global photoionization rate of the interstellar medium due to high-mass ($m > 10^3 M_\odot$), young ($\lesssim 10^7$ yr) O–B stars (Kennicutt 1983, 1990; Kennicutt et al. 1994). The total SFR can be determined by extrapolating the high-mass SFR to lower mass stars using an assumed IMF $\psi(m)$:

$$\psi(m) = \int_{M_{low}}^{M_{up}} \frac{M}{m} \, km^{-2} \, dm,$$

where $M_{up}$ ($M_{low}$) is the upper (lower) mass cutoff and $\alpha$ is the slope of the IMF. In the assumption that the SFR is

| Magnitude Limit | Objects | Hα | UV | CO | H I | H or K |
|----------------|---------|----|----|----|-----|--------|
| 11 .......... | 3       | 3  | 3  | 3  | 3   | 3      |
| 12 .......... | 8       | 8  | 6  | 8  | 8   | 8      |
| 13 .......... | 25      | 22 | 19 | 19 | 25  | 25     |
| 14 .......... | 45      | 29 | 27 | 23 | 45  | 42     |
| 15* ........ | 54      | 32 | 33 | 23 | 54  | 51     |
| 16* ........ | 59      | 35 | 34 | 23 | 59  | 56     |

Note.—Includes only objects with H I deficiency ≤0.3.

* Limited to the "ISO" sample.

| Magnitude Limit | Objects | Hα | UV | CO | H I | H or K |
|-----------------|---------|----|----|----|-----|--------|
| 14 ........... | 7       | 7  | 7  | 7  | 7   | 7      |
| 14.5 .......... | 20      | 20 | 5  | 17 | 20  | 20     |
| 15 .......... | 63      | 50 | 13 | 42 | 63  | 63     |
| 15.7 .......... | 174     | 117| 34 | 66 | 174 | 174    |

Note.—Includes only objects with H I deficiency ≤0.3.

| Type            | Objects | Hα or UV |
|-----------------|---------|----------|
| Sa              | 26      | 18       |
| Sab             | 14      | 13       |
| Sb              | 29      | 19       |
| Sbc             | 36      | 19       |
| Sc              | 66      | 50       |
| Scd             | 5       | 3        |
| Sd              | 3       | 2        |
| Sdm–Sd/Sm       | 2       | 2        |
| Sm              | 4       | 3        |
| Im–Im/S         | 3       | 2        |
| Pec             | 26      | 21       |
| S/BCD–DS/BCD    | 0       | 0        |
| Sm/BCD          | 2       | 2        |
| Im/BCD          | 1       | 0        |
| BCD             | 2       | 1        |
| S (dS)          | 12      | 5        |
| dim/DE          | 1       | 0        |
| Unknown         | 1       | 1        |
constant on a timescale of some $10^7$ yr, the SFR (in $M_\odot$ yr$^{-1}$) is given by the relation

$$SFR(M_\odot\text{ yr}^{-1}) = K_{\text{Hz}}(z, M_{\text{up}}, M_{\text{low}}) L_{\text{Hz}}(\text{erg s}^{-1})$$,

(2)

where $K_{\text{Hz}}(z, M_{\text{up}}, M_{\text{low}})$ is the proportionality constant between the Hz luminosity $L_{\text{Hz}}$ (in ergs s$^{-1}$) and the SFR$_{\text{Hz}}$ (in $M_\odot$ yr$^{-1}$). The value of $K_{\text{Hz}}(z, M_{\text{up}}, M_{\text{low}})$, which depends on the slope $z$ and on the upper and lower mass cutoffs $M_{\text{up}}$ and $M_{\text{low}}$ of the IMF, can be determined from models of stellar population synthesis. Different values of $K_{\text{Hz}}(z, M_{\text{up}}, M_{\text{low}})$ from the stellar population synthesis models of Charlot & Fall (1993) are given in Table 4, all for a lower mass cutoff $M_{\text{low}} = 0.1 M_\odot$ and solar metallicity.

The UV emission of a galaxy at 2000 Å is dominated by the emission of less recent ($\sim 10^8$ yr) and massive ($2 M_\odot < m < 5$) A stars (Lequeux 1989). The UV emission becomes significant if the SFR is constant over an interval of time as long as the lifetime of the emitting stars on the main sequence, i.e., $\geq 3 \times 10^8$ yr. Thus, assuming a SFR constant on timescales of some $10^8$ yr, the rate of star formation SFR$_{\text{UV}}$ from UV luminosities at 2000 Å ($L_{\text{UV}}$) can be determined from the relation

$$SFR_{\text{UV}}(M_\odot\text{ yr}^{-1}) = K_{\text{UV}}(z, M_{\text{up}}, M_{\text{low}}) L_{\text{UV}}(\text{erg s}^{-1})$$,

(3)

where $K_{\text{UV}}(z, M_{\text{up}}, M_{\text{low}})$ is the proportionality constant between the UV luminosity $L_{\text{UV}}$ (in ergs s$^{-1}$ Å$^{-1}$) and the SFR$_{\text{UV}}$ (in $M_\odot$ yr$^{-1}$). Values of $K_{\text{UV}}(z, M_{\text{up}})$ at 2000 Å for $M_{\text{low}} = 0.1 M_\odot$ and solar metallicity kindly made available from S. Charlot are listed in Table 4.

Hz and UV fluxes can thus be used independently to estimate the rate of star formation in galaxies once they are corrected for internal extinction and for the contribution of the [N II] emission line ($\lambda\lambda 6548, 6584$) that contaminates the narrowband Hz photometry. The corrections applied to the present data are described in the Appendix. As discussed there, the lack of far-IR data and of integrated spectra for all the sample galaxies prevents us from making accurate [N II] contamination and extinction corrections for each single galaxy, forcing us to use “statistical” corrections. Given the broad distribution in the UV and Hz extinctions measured by Buat & Xu (1996) and given in Figure 11 below for each morphological class, we estimate an uncertainty in the extinction correction of a factor of ~3 for each single galaxy, but probably lower for an entire class of objects. This uncertainty, which might be responsible for part of the observed scatter in several star formation indicators, such as the birthrate parameter, should not be critical in the forthcoming analysis, since it is significantly smaller than the whole range in star formation observed in the sample galaxies, which spans more than 3 orders of magnitude. From here on we estimate SFRs (in $M_\odot$ yr$^{-1}$) from UV and Hz luminosities using $K_{\text{UV}}(z, M_{\text{up}}, M_{\text{low}})$ and $K_{\text{Hz}}(z, M_{\text{up}}, M_{\text{low}})$ from Table 4 for $z = 2.5$, $M_{\text{up}} = 80 M_\odot$ and $M_{\text{low}} = 0.1 M_\odot$; for galaxies with both UV and Hz measurements (52 objects), the adopted SFR is an average of the results of the two methods.

### 3.2. The IMF

Since the Hz emission is due to massive ($m \geq 10 M_\odot$) O–B stars, and the UV emission to moderate-mass ($2 M_\odot \leq m \leq 5 M_\odot$) A stars, the two SFR determinations provide us with an indirect method for studying the IMF of spiral galaxies in the mass range $m \geq 2 M_\odot$ (Buat, Donas, & Deharveng 1987; Bell & Kennicutt 2001). This method can be applied only if the SFR has been constant over the last $3 \times 10^8$ yr, corresponding to the lifetime of stars dominating the UV emission on the main sequence. It is well known that this assumption applies for “normal” unperturbed objects, such as those selected here, while it does not hold for interacting systems (Kennicutt et al. 1987) and starburst galaxies.

For all galaxies in our sample with available Hz and UV data (52 objects), we compare in Figure 1 the ratio of the Hz to the UV fluxes, corrected for extinction and [N II] contamination as described in the Appendix, with the values determined from the stellar population synthesis models given in Table 4. Different symbols are used for disk-dominated (filled circles) and bulge-dominated (open circles) galaxies. The logarithm of the Hz-to-UV flux ratio is plotted versus the morphological type and the H luminosity.

The average value $\log [\text{flux Hz/flux UV}(2000 \text{ Å})] = 1.43 \pm 0.25$ is consistent with an IMF with slope $z = 2.5$ and $M_{\text{up}} = 80 M_\odot$, and it differs significantly from the values obtained for an IMF with slope 1.5 or 3.5 (see Table 4). Figure 1 shows that $\log [\text{flux Hz/flux UV}(2000 \text{ Å})]$ is independent of the morphological type, mass, and presence of a bulge. The value $z = 2.5$ is consistent with the Salpeter IMF ($z = 2.35$; Salpeter 1955). As shown in Figure 1, the Hz-to-UV flux ratio is more sensitive to the slope of the IMF than to $M_{\text{up}}$.

As discussed by Calzetti (2000), the Hz-to-UV flux ratio should increase with extinction in any fixed geometry. In the case of a slab model (absorbing dust and emitting stars well mixed in a disk), the observed Hz/UV (2800 Å) flux ratio overestimates the real value by a factor of 2 for typical Hz extinctions of ~1.1 mag (Calzetti 2000). This value has, however, to be taken as an upper limit since it has been observed that, despite a factor of ~4 in the Galactic extinction.

### Table 4

**Adopted IMF Parameters**

| IMF Slope | IMF Cutoff | $K_{\text{Hz}}(z, M_{\text{up}})$ | $K_{\text{UV}}(z, M_{\text{up}})$ | $\log [K_{\text{Hz}}(z, M_{\text{up}})/K_{\text{UV}}(z, M_{\text{up}})]$ |
|-----------|------------|-------------------------------|-------------------------------|-------------------------------------------------|
| 1.5...... | 80         | 1/[(1.61 × 10$^{42}$)]        | 1/(2.01 × 10$^{66}$)          | 1.903                                           |
| 2.5       | 40         | 1/[5.41 × 10$^{46}$]          | 1/3.18 × 10$^{99}$            | 1.231                                           |
| 3.5...... | 80         | 1/[1.16 × 10$^{41}$]          | 1/(3.54 × 10$^{99}$)          | 1.514                                           |

* From Charlot & Fall 1993, for $M_{\text{low}} = 0.1 M_\odot$, in units of $(M_\odot \text{ yr}^{-1})$/ergs s$^{-1}$.

b From S. Charlot 1996, private communication, for $M_{\text{low}} = 0.1 M_\odot$, in units of $(M_\odot \text{ yr}^{-1})$/ergs s$^{-1}$ Å$^{-1}$. 

tion law between 6563 and 2000 Å, UV and Hα extinctions are comparable because of less efficient absorption of the 2000 Å photons, dictated by the less concentrated distribution of the UV-emitting stars relative to the ionizing stars inside the dusty H II regions (see Appendix). We expect that variations in the extinction are responsible for an important fraction of the scatter in the Hα-to-UV flux ratio observed in Figure 1 without introducing any important second-order systematic effect (see Appendix).

An $\alpha = 2.5$ is in agreement with the value obtained by Buat et al. (1987), who analyzed 31 galaxies with Hα and UV data, adopting a method similar to the one used in this work, coupled with an older version of the evolutionary synthesis models. We do not confirm the trend they find with the morphological type, which might be contributed to by H II-deficient cluster galaxies which we deliberately excluded from our analysis.

4. STAR FORMATION HISTORY OF GALAXIES

4.1. The Birthrate Parameter

The birthrate parameter $b$ is defined by Kennicutt et al. (1994) as the ratio of the current SFR to the average past SFR. This distance-independent parameter $b$ is given by

$$b = \frac{SFR}{\langle SFR \rangle_{\text{past}}} = \frac{SFR t_0(1 - R)}{M_{\text{star}}},$$  \hspace{1cm} (4)

where $t_0$ and $M_{\text{star}}$ are the age and the total stellar mass of the disk, respectively, and $R$ is the fraction of gas that stars reinjected through stellar winds into the interstellar medium during their lifetime. While the SFR comes directly from the Hα and UV luminosities, the remaining parameters must be estimated indirectly. Since stars eject different fractions of gas into the ISM at different epochs of their life, the return parameter $R$ is a function of time and depends on the assumed IMF and birthrate history. Kennicutt et al. (1994) have shown that 90% of the returned gas is released in the first gigayear (more than half in the first 200 Myr) of a stellar generation for any assumed IMF. For this reason, we can safely assume an instantaneous recycling gas approximation in the determination of the birthrate parameter $b$, with a constant value $R = 0.3$, as determined by Kennicutt et al. (1994) for a Salpeter IMF.

The total stellar mass $M_{\text{star}}$ can be determined using the same procedure as described in Kennicutt et al. (1994), but using H-band luminosities instead of optical ones. Near-IR luminosities are directly proportional to the total dynamical masses ($M_{\text{tot}}/L_H = 4.6$) at the $B$-band 25 mag arcsec$^{-2}$ isophotal radius, independent of morphological type (Gavazzi et al. 1996b). The same $M_{\text{tot}}$ versus $L_H$ relationship is followed by BCDs, where, however, the near-IR flux may be contaminated by the emission of red supergiants; thus, even in these objects the H luminosity can be properly used as an estimator of the total mass.

Assuming $t_0 \sim 12$ Gyr, the birthrate parameter $b$ comes directly from

$$b = \frac{\text{SFR} t_0 (1 - R)}{L_H (M_{\text{tot}}/L_H) D_{\text{cont}}},$$  \hspace{1cm} (5)

where $D_{\text{cont}}$ is the dark matter contribution to the $M_{\text{tot}}/L_H$ ratio at the optical radius, which we assume to be 0.5, as in Kennicutt et al. (1994). As discussed by Rubin (1987), this value is independent of type and luminosity, and thus it should not introduce any systematic effect in the determination of $b$. Sandage (1986) and Kennicutt et al. (1994) have shown that the birthrate parameter, when determined using $B$ luminosities, increases along the Hubble sequence, but it is still not known how $b$ scales with mass.

The birthrate parameter (in logarithmic units) is plotted in Figure 2 versus the morphological type and the $H$ luminosity. Figure 2 shows a strong relationship between the birthrate parameter and these structural parameters, with late-type and dwarf galaxies (low-mass objects) all characterized by a similar present and past SFR ($b \sim 1$). There are a few galaxies with $b > 1$, i.e., with present SFR higher than that averaged over the past. These are low-mass dwarf galaxies that might undergo episodes of star bursts. Massive spirals, on the contrary, have present SFRs significantly lower than in the past ($b \sim 0.1$--0.01). The relationship between $b$ and the $H$ luminosity is however considerably clearer than that with the Hubble type, while only a systematic difference is observed between types $\lesssim$Sbc ($b \lesssim 0.25$) and types $\gtrsim$Scd ($b \gtrsim 0.25$), with Sc spanning the whole range in $b$.

If we limit our analysis to Virgo Cluster galaxies, for which the morphological classification is more accurate, we observe a less dispersed relation between $b$ and morphological type. A relationship between $b$ and the $H$ luminosity is however still observed inside any given morphological class, implying that part of the observed scatter in the $b$ versus...
type relationship is due to a stronger dependence of $b$ on the $H$ luminosity. On the other hand, part of the scatter in the $b$ versus log($L_{HI}$) relationship is due to the presence of a bulge; at any luminosity, galaxies with strong bulges ($C_31 > 3$, open circles) have lower birthrate parameters than pure exponential disks ($C_31 < 3$, filled circles).

4.2. The Gas Content of Galaxies

It is well known that the fraction of atomic gas increases along the Hubble sequence (Roberts & Haynes 1994 and references therein), but it is still unknown how the total gas mass (atomic plus molecular) scales with the total mass of galaxies. The line emission of $H\alpha$ at 21 cm and of $^{12}\text{CO}$ (1–0) at 2.6 mm can be used to estimate the total gas content ($H\alpha + H_2$) of the target galaxies.

The molecular hydrogen content can be estimated by assuming a constant ratio between the $^{12}\text{CO}$ (1–0) line emission and the $H_2$ surface density. In this work, we follow Boselli et al. (1997a) but adopt the CO-to-$H_2$ conversion factor $X = 1.0 \times 10^{20}$ molecules cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ of Digel et al. (1996). For galaxies with no CO measurement, we assume that the molecular hydrogen content is 10% of the $H\alpha$, as estimated from isolated spiral galaxies by Boselli et al. (1997a). The total gas mass is increased by 30% to take into account the helium contribution. The total gas content (normalized to the mass) of a galaxy depends strongly on the morphological type and on the $H$ luminosity, as shown in Figure 3. Late-type, low-mass galaxies have a larger amount of gas (per unit mass) than early-type, massive disks.

The relationship between log$(M_{gas}/L_H)$ and Hubble type has a slightly smaller dispersion if limited to the Virgo Cluster galaxies, which have more reliable morphological classifications. The relationship with the total mass is clearer than with the Hubble type. As for the birthrate parameter, we observe a trend between log$(M_{gas}/L_H)$ and $L_H$ inside each morphological class, implying that part of the scatter in the gas versus morphology relationship is due to the large scatter in the galactic mass within a given type. The residual of the log$(M_{gas}/L_H)$ versus $L_H$ relationship, however, is not correlated with the presence of a bulge.

4.3. Relation between Gas Content and the History of Star Formation in Galaxies

A relationship between the SFR and the gas density is known to exist locally within the disks of nearby late-type galaxies (Kennicutt 1989). Here we show that this relation extends to global quantities, integrated over the whole galaxy. This is not obvious a priori, since it is well known...
that most of the H I gas reservoir is located outside the optical disk of spiral galaxies, where star formation does not take place.

Figure 4 shows the relationship between the history of star formation as traced by the birthrate parameter and the total gas reservoir (per unit galaxy mass). Galaxies with \( b \approx 1 \) have large amounts of gas, while objects that formed most of their stars in the past \( (b \approx 0.1-0.01) \) have almost exhausted their gas reservoirs, becoming quiescent. Figure 4 shows a segregation between pure disks (filled circles) and bulge galaxies (open circles), the former being star-forming and gas-rich, the latter more quiescent and gas-poor.

4.4. Star Formation Efficiency and the Gas Consumption Timescale of Galaxies

The comparison of the current SFR with the gas content (atomic and molecular) gives an estimate of the efficiency of a given object to transform its gas reservoir into stars. The star formation efficiency (SFE) is defined as

\[
\text{SFE}(\text{yr}^{-1}) = \frac{\text{SFR}}{M_{\text{gas}}}. \tag{6}
\]

No relationship is observed between the SFE and the morphological type or the H luminosity (Fig. 5). Pure exponential disks (filled circles) have, on average, higher SFEs than bulge-dominated spirals (open circles) of similar H luminosity. If restricted to disk-dominated galaxies, a trend is observed, with low-mass galaxies having a lower SFE than giant disks.

The SFE can vary within a given morphological class by up to a factor of 10. The average value is \( 4 \times 10^{-10} \text{ yr}^{-1} \). The SFE is a time-independent quantity: it measures the instantaneous efficiency of transforming the gas into stars. Since the atomic gas has to go through the molecular phase to form stars inside molecular clouds, a more accurate measure of the SFE can be obtained if \( M_{\text{gas}} \) in equation (6) is replaced by the gas instantaneously contributing to the process of star formation, thus by \( M(\text{H}_2) \). Even using this modified definition of the SFE, we do not observe any relationship between the SFE and other structural parameters, in agreement with Rownd & Young (1999).

The SFE is proportional to the timescale for gas depletion if the fraction of gas ejected by stars and recycled is taken into account. This timescale, generally referred to as the "Roberts time," (Roberts 1963) is given by the relation

\[
\tau_R = \frac{M_{\text{gas}}}{\text{SFR}} \cdot \frac{1}{\text{SFE}} = \frac{1}{1-R} \tag{7}
\]

(Kennicutt et al. 1994), where \( R \) is the returned gas fraction. As discussed previously, the \( R \)-parameter changes with time, with the IMF, and with the birthrate history. The determination of the future evolution of the disk is strongly related to the dependence of \( R \) on the birthrate history of a galaxy. Kennicutt et al. (1994) have studied how \( (1-R)^{-1} \), the correction parameter for the determination of the Roberts time, changes for different IMFs, star formation laws (i.e., the relationship between the gas surface density and the SFR, known as the Schmidt law), and star formation efficiencies, these three variables being the most important parameters for the determination of the birthrate history of a galaxy. Their analysis shows that \( (1-R)^{-1} \) is in the range 1.5–4 for most star-forming disks characterized by a birthrate parameter \( b = 1-0.1 \), while it can be larger for rapidly evolving galaxies \( (b < 0.1) \) with low gas surface densities. Since the determination of \( R \) as a function of the star formation history of a galaxy is beyond the scope of the
The Roberts time is independent of the mass and the morphological type. This result is in contrast with that obtained by Donas et al. (1987), who observed a weak trend between the Roberts time and the morphological type, with the morphological type, with late-type systems the initial SFR was comparable to the present rate of star formation is lower than it was in the past. This is consistent with the idea that a rapid collapse might have induced a strong starburst, which efficiently transformed most of the gas into stars. The lack of gas at the present epoch makes these galaxies quiescent. Conversely, in objects with $b \sim 1$ (late-type, dwarf, low-mass galaxies) the gas is presently being transformed into stars at the same rate as in the past. This observational evidence is consistent with the model of galaxy formation discussed by Sandage (1986), who proposed that galaxies are coeval systems, formed from the collapse of a primordial gas cloud, with a collapse timescale depending on angular momentum. In elliptical galaxies, the collapse was efficient enough to transform most of the gas into stars within a few times $10^8$ yr. In late-type systems the initial SFR was comparable to the present one (a few solar masses per year), so that $\sim 10$ Gyr after the formation of the primeval galaxy a large fraction of the gas is still available to feed new stars. This idea was recently rediscussed by Gavazzi et al. (1996b), Gavazzi & Scodellino (1996), and Gavazzi et al. (1998). They observed that the $U-B$, $B-V$, UV $- B$ and $B-H$ color indexes and the $H\alpha$ equivalent width depend strongly on the galaxy mass. They interpreted this observational evidence as an indication that the total mass contributes to the regulation of the process of collapse of primeval gas clouds. This idea is also supported by recent numerical simulations by Noguchi (1999), which indicate that the bulge-to-disk ratio seems primarily regulated by the total mass of the galaxy. A

Point 1 is in agreement with the universality of the IMF in galaxies found in the high-mass stellar range of normal galaxies (Scalo 1986, 1998; Massey 1998). Recent results based on star counts in OB associations in the Magellanic Clouds seem to indicate that the IMF for massive stars is independent of metallicity (Hill, Madore, & Freedman 1994). No systematic differences have been observed in the IMFs of massive star associations in the Milky Way, LMC, or SMC (Hill et al. 1994; Massey et al. 1995; Hunter et al. 1996a, 1996b, or M33 (Hunter et al. 1996a); in all these nearby galaxies, the IMF has a slope consistent with $x = 2.5$ for masses less than $1 M_{\odot}$.

Points 2 and 3 have strong implications for models of galaxy formation and evolution. The importance of the $b$-parameter resides in the fact that it directly gives an idea of the history of star formation of a galaxy. In galaxies with a very small value of $b$ (generally early-type, massive galaxies), more of the stars have been formed at early epochs and the present rate of star formation is lower than it was in the past. This is consistent with the idea that a rapid collapse might have induced a strong starburst, which efficiently transformed most of the gas into stars. The lack of gas at the present epoch makes these galaxies quiescent. Conversely, in objects with $b \sim 1$ (late-type, dwarf, low-mass galaxies) the gas is presently being transformed into stars at the same rate as in the past. This observational evidence is consistent with the model of galaxy formation discussed by Sandage (1986), who proposed that galaxies are coeval systems, formed from the collapse of a primordial gas cloud, with a collapse timescale depending on angular momentum. In elliptical galaxies, the collapse was efficient enough to transform most of the gas into stars within a few times $10^8$ yr. In late-type systems the initial SFR was comparable to the present one (a few solar masses per year), so that $\sim 10$ Gyr after the formation of the primeval galaxy a large fraction of the gas is still available to feed new stars. This idea was recently rediscussed by Gavazzi et al. (1996b), Gavazzi & Scodellino (1996), and Gavazzi et al. (1998). They observed that the $U-B$, $B-V$, UV $- B$ and $B-H$ color indexes and the $H\alpha$ equivalent width depend strongly on the galaxy mass. They interpreted this observational evidence as an indication that the total mass contributes to the regulation of the process of collapse of primeval gas clouds. This idea is also supported by recent numerical simulations by Noguchi (1999), which indicate that the bulge-to-disk ratio seems primarily regulated by the total mass of the galaxy. A

5. A MODEL OF THE STAR FORMATION HISTORY

Let us summarize the evidence collected so far:

1. Photometric $H\alpha$ and UV (2000 Å) measurements of 52 late-type (Sa–Im–BCD) galaxies, combined with spectral evolution models, show that the IMF of galaxies is consistent with a Salpeter IMF of slope $x = 2.35$ and an upper mass cutoff of about $80 M_{\odot}$ in the mass range $m > 2 M_{\odot}$. Galaxies of different morphology and luminosity seem to have similar IMFs.

2. The birthrate parameter $b$, which gives the present-to-past SFR ratio ($SFR/\langle SFR\rangle_{\text{past}}$), is strongly correlated with the total mass of galaxies as traced by their near-IR luminosity; the relationship between $b$ and the morphological type is weaker than with $L_{\text{H}}$

3. The total gas reservoir per unit mass is anticorrelated with the total mass of galaxies; as for $b$, the relationships between $M_{\text{gas}}/L_{\text{H}}$ and the morphological type are more dispersed than with $L_{\text{H}}$. Low-mass dwarf galaxies, which are generally pure exponential disks, have a higher gas content per unit mass and present-to-past SFRs than early-type, massive spirals.

4. The birthrate parameter $b$ correlates with the total gas content of galaxies.

5. The SFE and the timescale for gas depletion do not strongly correlate with properties of galaxies such as the luminosity and the morphological type. If limited to pure disks, however, a trend between SFE and the total galaxy mass is observed. The timescale for gas depletion is $\sim 10$ Gyr for normal, unperturbed late-type galaxies.

Point 1 is in agreement with the universality of the IMF in galaxies found in the high-mass stellar range of normal galaxies (Scalo 1986, 1998; Massey 1998). Recent results based on star counts in OB associations in the Magellanic Clouds seem to indicate that the IMF for massive stars is independent of metallicity (Hill, Madore, & Freedman 1994). No systematic differences have been observed in the IMFs of massive star associations in the Milky Way, LMC, or SMC (Hill et al. 1994; Massey et al. 1995; Hunter et al. 1996a, 1996b, or M33 (Hunter et al. 1996a); in all these nearby galaxies, the IMF has a slope consistent with $x = 2.5$ for masses less than $1 M_{\odot}$.

Points 2 and 3 have strong implications for models of galaxy formation and evolution. The importance of the $b$-parameter resides in the fact that it directly gives an idea of the history of star formation of a galaxy. In galaxies with a very small value of $b$ (generally early-type, massive galaxies), more of the stars have been formed at early epochs and the present rate of star formation is lower than it was in the past. This is consistent with the idea that a rapid collapse might have induced a strong starburst, which efficiently transformed most of the gas into stars. The lack of gas at the present epoch makes these galaxies quiescent. Conversely, in objects with $b \sim 1$ (late-type, dwarf, low-mass galaxies) the gas is presently being transformed into stars at the same rate as in the past. This observational evidence is consistent with the model of galaxy formation discussed by Sandage (1986), who proposed that galaxies are coeval systems, formed from the collapse of a primordial gas cloud, with a collapse timescale depending on angular momentum. In elliptical galaxies, the collapse was efficient enough to transform most of the gas into stars within a few times $10^8$ yr. In late-type systems the initial SFR was comparable to the present one (a few solar masses per year), so that $\sim 10$ Gyr after the formation of the primeval galaxy a large fraction of the gas is still available to feed new stars. This idea was recently rediscussed by Gavazzi et al. (1996b), Gavazzi & Scodellino (1996), and Gavazzi et al. (1998). They observed that the $U-B$, $B-V$, UV $- B$ and $B-H$ color indexes and the $H\alpha$ equivalent width depend strongly on the galaxy mass. They interpreted this observational evidence as an indication that the total mass contributes to the regulation of the process of collapse of primeval gas clouds. This idea is also supported by recent numerical simulations by Noguchi (1999), which indicate that the bulge-to-disk ratio seems primarily regulated by the total mass of the galaxy. A
that all the returned gas is used to form stars). If we assume a closed-box scenario, we can assume that of Kennicutt et al. (1994).

The values of \( q \) and \( b \) respectively the total gas, \( t \) and \( \tau \) are the timescale for collapse, and \( \text{SFR}_0 \) is the rate of star formation at the time of the galaxy formation (\( t = 0 \)). They found small values of \( \tau \) (\( \tau \sim 0.5 \) Gyr) for giant disks and large values (\( \tau \sim 10 \) Gyr) for low-mass objects.

The observational results of the present work are consistent with this simple picture. Let us assume that galaxies evolve as closed boxes following a star formation law of the type described in equation (8), but assuming a more realistic age of \( t_0 = 12 \) Gyr.

\[
M_{\text{star}}(t) = (1 - R) \int_0^t \text{SFR}_0 e^{-\tau \bar{t}} \, dt',
\]

which can be directly measured from the \( H \)-band luminosity as described in §4.1.\(^1\)

\[
M_{\text{star}}(t) = L_H(t) DM_{\text{cont}}(t)[M_{\text{tot}}/L_H(t)],
\]

given the fact that the \( H \) luminosity traces the total dynamical mass of galaxies. \( \text{SFR}_0 \) gives the number of stars formed per year at the formation of the galaxy. Its dependence on the total mass implies that the process of collapse is not scale-free. To simplify the formalism, we define \( X(t) = DM_{\text{cont}}(t)[M_{\text{tot}}/L_H] \). As discussed in §3.2, \( X(t) = 0.5 \times 4.6 \) at \( t = t_0 = 12 \) Gyr.

Combining equation (5) with equations (8) and (9), we can directly estimate the birthrate parameter \( b \) as a function of \( t \) and \( \tau \):

\[
b(t) = \frac{t e^{-\tau \bar{t}}}{\tau (1 - e^{-\tau \bar{t}})},
\]

The values of \( b \) obtained from equation (11) for different values of \( \tau \) and assuming \( t = t_0 = 12 \) Gyr are consistent with those obtained from the population synthesis models of Kennicutt et al. (1994).

If \( M_{\text{tot}} \) is the total mass of a galaxy (constant with time in a closed-box scenario), we can assume that

\[
M_{\text{tot}} = M_{\text{gas}}(t) + M_{\text{star}}(t) + M_{\text{DM}}(t)
\]

for all \( t \),

where \( M_{\text{gas}} \), \( M_{\text{star}} \), and \( M_{\text{DM}} \) are respectively the total gas, stellar, and dark matter masses at time \( t \).

If we assume that all the gas will in the future be transformed into stars, for \( t \to \infty \), \( M_{\text{gas}}(t) \to 0 \), while \( M_{\text{star}}(t) = 0 \) for \( t = 0 \), and thus

\[
M_{\text{star}}(\infty) = M_{\text{gas}}(0) = M_{\text{tot}} - M_{\text{DM}}(0) = \text{SFR}_0 \tau
\]

(assuming that all the returned gas is used to form stars). If we assume that \( M_{\text{DM}} \) does not change with time, \( M_{\text{gas}}(t) \) can be determined from equation (12). By substituting \( \text{SFR}_0 \tau \) for \( M_{\text{tot}} - M_{\text{DM}} \), equation (12) becomes

\[
M_{\text{gas}}(t) = \text{SFR}_0 \tau e^{-\tau \bar{t}},
\]

\[
\frac{M_{\text{gas}}(t)}{L_H(t)} = \frac{X(t)(1 - R)}{1 - R} e^{-\tau \bar{t}}
\]

under the assumption that \( R \) does not change with time.

At the same time, this simple model predicts that the SFE defined in equation (6) should be

\[
\text{SFE} = \tau^{-1}
\]

and, thus, independent of \( t \). This means that each galaxy should have had an efficiency in transforming gas into stars that depends only on the \( \tau \)-parameter, but similar at any epoch.

This analytic representation of all the observed variables used in this work (SFR, \( b \), \( M_{\text{gas}}/L_H \), SFE) can be done once a star formation law such as that given in equation (8) is assumed.\(^2\) The analytical model can be compared with the observables only once \( \text{SFR}_0 \) is known, \( L_H \) being a function of \( \text{SFR}_0 \); the other variables (\( b \), \( M_{\text{gas}}/L_H \), SFE), being normalized entities, do not depend on \( \text{SFR}_0 \). This parameter, which gives the rate of star formation at the time of the galaxy formation (\( t = 0 \)), is clearly dependent on the mass of the galaxy (\( \text{SFR}_0 \tau = M_{\text{star}} + M_{\text{gas}} \)).

Following Gavazzi & Scodelligo (1996), if we assume a simple empirical relationship between the \( H \)-luminosity and the exponential decay timescale for star formation of the type

\[
\log L_H = a \log \tau + c,
\]

can derive from equations (9) and (10) a semianalytical relationship between \( \text{SFR}_0 \) and \( \tau \):

\[
\text{SFR}_0 = \frac{X(t_0) e^{10^c}}{(1 - R) e^{-\tau \bar{t}}}. \tag{17}
\]

Once \( \text{SFR}_0 \) is determined, we can compare the predictions of the analytical models with the relationships previously discussed between \( b \), \( M_{\text{gas}}/L_H \), or SFR and the \( H \)-band luminosity (Figs. 7a, 7b, and 7d). The model prediction (dotted lines) can be directly compared with the observations for the \( M_{\text{gas}}/L_H \) versus \( b \) relationship (Fig. 7c), without any assumption on the relationship between \( \tau \) and \( L_H \), both being normalized entities and thus independent of \( \text{SFR}_0 \). At the same time, the obvious observed scaling relationships between SFR, \( M_{\text{gas}} \), and \( L_H \) can be compared with the model’s prediction (Figs. 7e and 7f) and used, together with the normalized entities, to constrain the free parameters \( a \) and \( c \). An excellent fit to the data is obtained for \( a = -2.5 \) and \( c = 12 \) once \( \tau \) is expressed in gigayears, consistent with Gavazzi & Scodelligo (1996; \( a = -2.5 \), \( c = 11.12 \)).

In conclusion, the observed relationships between optical, near-IR, and UV colors, Hz equivalent widths, the birthrate parameter \( b \), the total gas mass, and the \( H \) luminosity were obtained by Boissier & Prantzos (2000) and Boissier et al. (2001), whose chemi-spectrophotometric models of galaxy evolution reproduce several observed properties of disk galaxies only when the gas infall (and thus the star formation activity) is regulated by the total mass of the galaxy.

Under the assumption that galaxies are coeval, and that they evolved as closed boxes, Gavazzi & Scodelligo (1996) and Gavazzi et al. (1998) were able to reproduce the relationships between the color indexes, the Hz equivalent widths, and the \( H \) luminosities, using the population synthesis models of Bruzual & Charlot (1993) and Kennicutt et al. (1994) and adopting a star formation law of the type

\[
\text{SFR}(t) = \text{SFR}_0 e^{-\tau \bar{t}} \, M_\odot \, \text{yr}^{-1} \tag{8}
\]

with a Salpeter IMF, where \( t \) is the age of the galaxy, \( \tau \) is the timescale for collapse, and \( \text{SFR}_0 \) is the rate of star formation at the time of the galaxy formation (\( t = 0 \)). They found small values of \( \tau \) (\( \tau \sim 0.5 \) Gyr) for giant disks and large values (\( \tau \sim 10 \) Gyr) for low-mass objects.

\(^{1}\) As discussed in §4.1, \( R \) can be taken as a constant for \( t > 1 \) Gyr.

\(^{2}\) We have repeated this exercise replacing the exponential star formation law (eq. [8]) with a “delayed exponential” law, such as that proposed by Sandage (1986). This law better accounts for cases with increasing SFR with time, as observed in some irregular galaxies such as I Zw 18 (Kunth & Ostri 2000). We found results qualitatively consistent with the exponential case; thus, we avoid expanding the “delayed exponential” case in full detail.
nosity can, at least to first order, be reproduced with the simple assumption that galaxies are coeval (∼12 Gyr), that they evolved as closed boxes following an exponentially declining star formation law, with a decay timescale depending on the mass of the primeval cloud—small (τ ∼ 0.5 Gyr) for massive objects ($L_H = 10^{12} L_{\odot}$) and large (τ ∼ 10 Gyr) for dwarf systems ($L_H = 10^9 L_{\odot}$).

If the models discussed here are realistic, we conclude that the strong relationship observed between various star formation tracers, such as the UV flux (Donas et al. 1990; Deharveng et al. 1994; Buat 1992; Boselli 1994), the Hα flux (Kennicutt 1989, 1998; Scodeggio & Gavazzi 1993 and references therein), and the H I or total gas surface density in unresolved galaxies is not due to a local relationship between the gas column density and the process of star formation, known as the Schmidt law, but is simply a consequence of the closed-box evolution. From equations (8) and (13) we expect in fact that the integrated SFR and the total gas content decrease with time with a similar decline. This conclusion is corroborated by the fact that in “normal,” unperturbed galaxies the H I gas (which constitutes ∼90% of the total gas reservoir; Boselli et al. 1997a) is found in a flat disk of diameter about twice as large as the optical one (Cayatte et al. 1990). This gas is not expected to contribute directly to the star formation, since (1) up to 75% of the H I reservoir is located outside the optical disk, where the star

Fig. 7.—Comparison between the model prediction and observations for the (a) b vs. log $L_H$, (b) log ($M_{\text{gas}}/L_H$) vs. log $L_H$, (c) b vs. log ($M_{\text{gas}}/L_H$), (d) SFE vs. log $L_H$, (e) SFR vs. log $L_H$, and (f) $M_{\text{gas}}$ vs. log $L_H$ relationships. Symbols are as in Fig. 1.
formation takes place, and (2) the H\textsc{i} has to go through the molecular phase before forming stars. Thus, an inflow of gas from the outer H\textsc{i} disk to the optical disk must be present. Spiral galaxies of all morphological types and luminosity still have enough gas to continue their present-day star formation activity for $\sim 10$ Gyr. This time is significantly longer than previous estimates because we assume a higher contribution of the recycled gas (see Kennicutt et al. 1994) and because the H\textsc{i}-deficient cluster galaxies are excluded from the analysis (Boselli 1998).

6. COMPARISON WITH OBSERVATIONS AT HIGH REDSHIFT

The aim of this section is to discuss whether the closed-box scenario discussed in the present paper, based on observations of local “adult” late-type galaxies, is consistent with observations at higher redshift.

Several recent attempts to reconstruct the evolution with look-back time of the total star formation activity of the universe (Cowie, Songaila, & Barger 1999; Steidel et al. 1999; Madau, Pozzetti, & Dickinson 1998 and references therein) unaniomously concluded that it increases by about an order of magnitude from $z = 0$ to $z \sim 1$. The dependence for $z > 1$ is more controversial; however, the most recent determination by Steidel et al. (1999) indicates that, if the data are appropriately corrected for extinction, the star formation activity of the universe remains roughly constant for larger look-back times, up to $z \sim 4$.

Equation (8), together with equation (16), gives the time evolution of the SFR of galaxies of luminosity $L_B$, for a given SFR$_0$. We can predict, for a galaxy of a given H luminosity at $z = 0$, its SFR at any $z$. We can then estimate the SFR per unit comoving volume of the universe by integrating the contribution to the SFR of each galaxy, weighted according to a given luminosity function. Since we are dealing with late-type galaxies, we assume the local $B$-band Schechter luminosity function of Heyl et al. (1997) for types Sa–Sm and transform $B$ magnitudes into $H$ magnitudes assuming the $B - H$ versus $B$ color-magnitude relation

$$B - H = 7.7 - 0.38 B,$$

as determined from the subsample of Virgo late-type galaxies, which spans the full dynamic range in luminosity.

The resulting SFR per comoving volume of the universe is compared with the observed SFR as a function of $z$ in Figure 8. For consistency with previous work, we assume $\Lambda = 0$, $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, and $q_0 = 0.5$. The “observed” values of SFR (in $M_\odot$ yr$^{-1}$ Mpc$^{-3}$) from Steidel et al. (1999, open symbols) are corrected for extinction. The values of the 2800 Å luminosity density given by Cowie et al. (1999, filled squares) are transformed into $M_\odot$ yr$^{-1}$ Mpc$^{-3}$ and corrected for extinction consistently with Steidel et al. (1999). The values from Treyer et al. (1998, filled triangle) and Gallego et al. (1996, filled circle), obtained respectively from the local UV at 2000 Å and H$\alpha$ luminosity functions, are also transformed into $M_\odot$ yr$^{-1}$ Mpc$^{-3}$ as described in §3, adopting for simplicity an extinction correction of 0.3 mag. Such a small UV and H$\alpha$ extinction derives from the assumption that the UV and H$\alpha$ luminosity functions are dominated by low-mass, low-luminosity, blue galaxies (see Appendix). Figure 8 shows that, at least qualitatively, the model predictions give an excellent fit to the updated estimates of the SFR per comoving volume.

Our model (dotted line) is in excellent agreement with the points at $z = 0$ from Gallego et al. (1996, filled circle) and Treyer et al. (1998). It accurately reproduces the relation SFR(Mpc$^{-3}$) $\propto (1 + z)^{1.5}$ observed by Cowie et al. (1999) in the range $0 < z < 1.5$ (filled squares) and is consistent with the extinction-corrected estimates of Steidel et al. (1999) for $3 < z < 4.5$.

It is remarkable that the predicted SFRs are in agreement with the observations even though we consider only the contribution of the late-type galaxies to the evolution of the SFR of the universe. One should remember however that the adopted SFRs per comoving volume, with which we compare our model predictions, have all been estimated from UV-selected samples and thus are biased toward low-extinction galaxies. Elliptical galaxies, which are expected to be formed in violent starbursts with strong dust extinction, should not be present in UV-selected samples. Their contribution at early epochs should however be observable in the millimeter domain (Franceschini et al. 1994).

Using a similar procedure, we can compare the model predictions with the observed comoving density of the gas, as determined from observations of damped Ly$\alpha$ systems. As above, the contribution to the total gas density of the universe is weighted according to the $B$ luminosity function of Heyl et al. (1997), and $B$ magnitudes are transformed into $H$ magnitudes using equation (18). The $\tau$-parameter in equation (13) is constrained by the relationship between $\tau$ and the $H$ luminosity given in equation (16) (with $a = -2.5$ and $c = 12$). The gas density of the universe at different epochs can be estimated by integrating the derived “gas mass” luminosity function.

The model predictions are found to be in remarkable agreement (see Fig. 9) with the gas density of the universe $\Omega_g$ (expressed in units of the present critical density) as determined from the statistical analyses of damped Ly$\alpha$ systems by Pei, Fall, & Hauser (1999) and Rao & Turnshek (2000). We use the values of $\Omega_g$ given by Pei et al. (1999) corrected...
to take into account the missing damped Ly\textalpha{} systems for dust obscuration in an optically selected sample of quasars. To be consistent with Pei et al., we removed the contribution of H\textsubscript{2} (10%) to the values of $\Omega_{g}$ estimated from our model. Both models predict a gas density of the universe at $z=0$ approximately 4 times higher than the observed value determined from the local H\textsc{i} luminosity function of Zwaan et al. (1997); this is due to the fact that the model overestimates the gas content of low-luminosity galaxies (see Fig. 7f), whose contribution to the local luminosity function is dominant.

The agreement between $\Omega_{g}$ predicted by our model and the result of the statistical analysis of damped Ly\textalpha{} systems is good at redshifts less than 2, while it becomes poor at higher $z$. The determination of $\Omega_{g}$ at $z>1.5$ strongly depends on the adopted correction for missing absorbers at high redshifts and thus, as for the SFR, on the variation of the dust-to-gas ratio with $z$. The disagreement between the model prediction and $\Omega_{g}$ for $z>2$ could thus be due to an underestimate of the extinction bias at high redshifts in the optically selected sample of quasars.\textsuperscript{3} Pei et al. (1999) interpret the decrease of $\Omega_{g}$ with $z$ as being due to the fact that dampedLy\textalpha{} systems are galaxies that grow by accretion of (essentially ionized) gas. This would result in a decrease of the comoving neutral gas density of the universe with redshift. Our closed-box model cannot reproduce any decrease of $\Omega_{g}$ with $z$, since the gas is always assumed to be in the neutral phase.

We remark that the model predictions at high redshift depend strongly on the parameters $a$ and $c$ of equation (16) and on the assumed $B$ luminosity function. Furthermore, the absolute value of the SFR (Mpc$^{-3}$) at different $z$ might change by a factor of $\sim 2$ when adopting different population synthesis models.

To summarize, this work has shown the importance of mass in parameterizing most of the physical properties of nearby galaxies. The history of star formation and the amount of total gas (per unit mass) of galaxies are found to depend primarily on their total mass and only secondarily on their morphological type. This strong observational evidence must be reproduced by models of galaxy formation and evolution.

The analysis carried out in the present paper can be considered an exercise aimed at showing that the "monolithic" scenario of galaxy formation is not yet observationally falsified, both on local and on cosmological scales. Several scaling relations observed in nearby galaxies (i.e., the gas content, the activity of star formation, and the stellar populations) can be reproduced by assuming that galaxies are coeval and that they evolved as closed boxes with a universal star formation law whose characteristic timescale parameter $\tau$ scales inversely with the total mass of the parent galaxies. The same scenario predicts a look-back time dependence of the integrated star formation activity and gas content of the universe consistent with the observations up to large redshifts. In order to reproduce the observed local properties of galaxies and the cosmological dependences discussed above, we see no compelling need for more sophisticated galaxy formation models, such as the hierarchical model proposed by Kauffmann, White, & Guiderdoni (1993) and by Cole et al. (1994).

The present work seems to indicate that the evolution of the SFR and the gas density of the universe is due to gas consumption via star formation processes according to a simple, universal star formation law, independent of $z$, valid for all rotating systems. Besides any cosmological speculation, the firm conclusion of the present work is that the history of the star formation of disk galaxies is primarily regulated by their total mass and only secondarily by their angular momentum.

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APPENDIX

CORRECTIONS TO H\textalpha{} + [N\textsc{ii}] AND UV FLUXES

A1. [N\textsc{ii}] CONTAMINATION

The analysis of the integrated spectra of late-type galaxies by Kennicutt (1992) has shown that, on average, the [N\textsc{ii}]
total UV emission at 2000 Å is diffuse, even though part of the diffuse emission might be scattered light. Given the complex distribution of absorbing dust and emitting stars, the determination of the fraction of scattered light in spiral galaxies is very uncertain; however, the models of Witt & Gordon (2000) indicate that the scattered light in the UV at 2000 Å is ~20% once a clumpy geometry is assumed. Furthermore, the observations of nearby galaxies are limited to few late-type spirals, preventing us from quantifying the contribution of the diffuse emission to the total UV emission in early-type spirals. It is however conceivable that in Sa’s the diffuse emission contribution is even higher than in Scd galaxies such as M33. Since dust is mostly associated with H II regions, the relative geometric distribution of absorbing dust and emitting stars, which increases the absorption of Hz with respect to UV photons at 2000 Å, should compensate the ~4 times higher UV extinction with respect to extinction at Hz.

From the analysis of the Balmer decrement of a large sample of galaxies with long-slit integrated spectroscopy, Kennicutt (1992) estimated that the average extinction of the Hz flux of late-type galaxies is ~1 mag. Consistently, the comparison of free-free radio fluxes and Hz fluxes of normal galaxies by Kennicutt (1983) indicates an extinction of 1.1 mag. In order to study whether the Hz extinction is dependent on morphological type, we have reexamined the sample of Kennicutt (1992) limited to “normal” galaxies (thus excluding Markarian objects), dividing galaxies in two subsamples: types Sa–Scd and types Sd and later. High-resolution spectra were selected as first priority. The extinction of the Hz flux strongly depends on the assumption for the underlying Balmer absorption, in particular in normal galaxies, where the Hβ line is generally weak. Values found in the literature range between 2 and 5 Å in Hβ equivalent width (Kennicutt 1992; McCall, Rybksi, & Shields 1985). We calculate for simplicity the Hz extinction using these two values of the underlying Balmer absorption. Including this correction and following the prescription of Lequeux et al. (1981), we can estimate that the extinction at a given λ from the Balmer decrement is

\[ A(\lambda) = 2.5C(\lambda), \]

where

\[ C(Hz) = 1 \int (Hz) \left( \frac{I(Hz)}{F(Hz)} - \frac{I(H\beta)}{F(H\beta)} - \log \left( \frac{E}{H\beta} \right) \right), \]

where \( I(Hz) \) is the Galactic reddening function normalized at Hβ, \( f(Hz) = -0.355 \) (Lequeux et al. 1981), \( I(Hz) \) and \( I(H\beta) \) are the extinction-corrected intensities, and \( F(Hz) \) and \( F(H\beta) \) are the observed intensities of the Hz and Hβ lines. \( E \) is the underlying Balmer absorption (in angstroms). Assuming a ratio of \( I(Hz)/I(H\beta) = 2.86 \) for a case B nebula at 104 K (Brocklehurst 1971), we obtain average values for the Hz extinction of \( A(Hz) = 0.78 \pm 0.47 \) (for \( E = 5 \) Å) and \( A(Hz) = 1.60 \pm 0.77 \) (for \( E = 2 \) Å) for spirals, and \( A(Hz) = 0.41 \pm 0.29 \) (for \( E = 5 \) Å) and \( A(Hz) = 0.86 \pm 0.42 \) (for \( E = 2 \) Å) for galaxies with types Sd and later (see Fig. 11).

We did not observe any relation of \( A(Hz) \) or Hz surface brightness (extended to all the galaxies of our sample) with inclination, even once galaxies were divided into different
morphological class bins. We stress, however, the fact that the sample of Kennicutt (1992) is biased toward strongly star-forming galaxies, even if Markarian galaxies are excluded, and thus it might not be representative of the sample of galaxies analyzed in this work. In fact, the average Hα [N II] equivalent width in the sample of Kennicutt (1992) is 82 Å for spirals and 105 Å for types Sd and later, while in the sample analyzed in this work, the average values are Hα [N II] EW = 22 Å and Hα [N II] EW = 46 Å, respectively. In conclusion, we decided to assume a standard Hα extinction correction of 1.1 mag for types Sa–Scd, and 0.6 mag for types Sd and later.

The lack of any relationship between the UV surface brightness and inclination observed for our sample galaxies prevents us from estimating an inclination-dependent extinction correction law. As shown by Buat & Xu (1996), the UV extinction at 2000 Å is ~0.9 mag for galaxies with types Scd and earlier and ~0.2 for galaxies with types Sd and later. If, however, the ratio between the Hα (corrected for [N II] contamination) and the UV fluxes for galaxies with types Sa–Scd is plotted versus their axial ratio, a residual trend is still marginally present (see Fig. 12).

A linear fit to this relation yields

$$\log \left( \frac{L_{\text{Hα}}}{L_{\text{UV}}} \right) = -0.56 \log \left( \frac{b}{a} \right) + 1.24 \quad , \quad \text{(A3)}$$

where log(b/a) is the axial ratio. If we make the reasonable assumption that this trend is due to increasing extinction with inclination, this relation can be used to determine an empirical correction to the UV data as a function of the axial ratio. This correction, however, represents a lower limit since it has been determined assuming that the Hα extinction is independent of the galaxy inclination. For a random distribution of b/a, we derive an average UV extinction of A(UV) ~ 0.3 mag. In order to be consistent with Buat & Xu (1996), we assume

$$A_{\text{(UV)}} = A_{\text{(UV)}}^{\text{face-on(type)}} - k_i \text{(type)} \log \left( \frac{b}{a} \right) , \quad \text{(A4)}$$

where the values of A(UV)_{face-on} and k_i are given in Table 5 for different morphological classes. Given the systematic difference in luminosity between spirals and dwarfs, the adopted corrections take into account, at least to first order, a possible dependence between extinction and luminosity.

### TABLE 5

| Type            | A(Hα)_{face-on} | A(UV)_{face-on} | k_i (type) |
|-----------------|-----------------|-----------------|------------|
| Sa–Scd (Pec, S... at D > 30 Mpc) | 1.1             | 0.60            | 0.56       |
| Sd–Im–BCD       | 0.6             | 0.20            | 0.00       |

The relationship between the Hα-to-UV flux ratio and axial ratio. The dashed line shows the best fit to the data.

Fig. 12.—Relationship between the Hα-to-UV flux ratio and axial ratio. The dashed line shows the best fit to the data.
