THE COSMIC EVOLUTION OF THE GALAXY LUMINOSITY DENSITY

Francesco Calura and Francesca Matteucci

Dipartimento di Astronomia, Università di Trieste, via G. B. Tiepolo 11, I-34131 Trieste, Italy; fcalura@ts.astro.it, matteucci@ts.astro.it

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ABSTRACT
We reconstruct the history of the cosmic star formation in the universe by means of detailed chemical evolution models for galaxies of different morphological types. We consider a picture of coeval noninteracting evolving galaxies in which elliptical galaxies experience intense and rapid starbursts within the first gigayears after their formation and spiral and irregular galaxies continue to form stars at lower rates up to the present time. Such models allow one to follow in detail the evolution of the metallicity of the gas from which the stars are formed. We normalize the galaxy population to the $B$-band luminosity function observed in the local universe and study the redshift evolution of the luminosity densities in the $B$, $U$, $I$, and $K$ bands, calculating galaxy colors and evolutionary corrections by means of a detailed synthetic stellar population model. Our predictions indicate that the decline of the galaxy luminosity density between redshift 1 and 0 observed in the $U$, $B$, and $I$ bands is caused mainly by star-forming spiral galaxies that slowly exhaust their gas reservoirs. Elliptical galaxies have dominated the total luminosity density in all optical bands at early epochs, when all their stars formed by means of rapid and very intense starbursts. Irregular galaxies bring a negligible contribution to the total luminosity density in any band at any time. We study the cosmic missing-metal crisis and conclude that it could be even more serious than what has been assessed by previous authors, if the bulk of the metals were produced in dust-obscured starbursts associated with the early spheroid formation. The most plausible site for the missing metals could be the warm gas in galaxy groups and protoclusters, in which the metals could have been ejected through galactic winds following intense starbursts. Finally, we predict the evolution of the cosmic star formation and supernova II and Ia rates and obtain the best fit to the observations, assuming a Salpeter initial mass function. All our results indicate that the bulk of the stellar mass in most galaxies were already in place at early epochs, and we predict a peak in the global star formation rate at high redshift because of elliptical galaxies.

Subject headings: galaxies: evolution — galaxies: fundamental parameters — galaxies: high-redshift — galaxies: photometry

1. INTRODUCTION

The study of the evolution of the galaxy luminosity density is fundamental to understanding how galactic structures formed and evolved in the universe. The light emitted by stars of various masses at various wavelengths can provide different indications concerning how the cosmic star formation history proceeded in the past and concerning the fraction of baryons locked up in stars and gas in the local universe. The short-wavelength light, i.e., that emitted in the rest-frame $U$ and $B$ bands, is mainly radiated by short-lived massive stars; thus, it can be a direct tracer of star formation. On the other hand, the near-infrared light is primarily emitted by low-mass, long-lived stars, which contribute to the bulk of the total stellar mass; hence, it traces the mass distribution of galaxies. Several attempts to model the cosmic history of star formation and the evolution of the luminosity density have been performed, generally following different routes. One way to reconstruct the evolution of galaxies is often referred to as the “traditional” scheme, in which galaxy densities are normalized according to the optical and IR luminosity functions observed at $z = 0$. The adoption of a star formation history and a cosmological model allows one to follow the redshift evolution of the luminosity density, as well as to reconstruct other properties, such as number counts and color distributions (Totani, Yoshii, & Sato 1997; Pozzetti et al. 1998; Tan, Silk, & Ballard 1999; Jimenez & Kashlinsky 1999; Totani & Takeuchi 2002). A different approach is followed by Madau, Pozzetti, & Dickinson (1998b), who start from the observed time-dependent star formation rate (SFR) per unit comoving volume and an initial mass function (IMF) and then model the luminosity density by means of a photometric code. Fall, Charlot, & Pei (1996) compute the evolution of the total cosmic emissivity and of the background intensity on the basis of quasar absorption-line studies, i.e., H I and metallicity data observed in damped Lyα (DLA) systems, combined with cosmic chemical evolution (Pei & Fall 1995) and stellar population models (see also Sadat, Guiderdoni, & Silk 2001 and Boselli et al. 2001 for similar approaches). Other groups compute the cosmic star formation history by using large-scale hydrodynamical simulations (Nagamine, Cen, & Ostriker 2000; Ascasibar et al. 2002) or semianalytical models of galaxy formation (Baugh et al. 1998; Cole et al. 2000; Somerville, Primack, & Faber 2001), both methods based on the cold dark matter paradigm. An interesting alternative is the approach by Rowan-Robinson (2001), in which the star formation rate is parameterized to investigate the effects that the choice of these parameters have on the far-infrared and submillimeter counts and background radiation. However, most of the approaches described above cannot predict the roles of the different galactic morphological types at various cosmic epochs and which type of galaxy determines the rapid
evolution observed in the luminosity density between \( z = 0 \) and 1. In this paper, we calculate the evolution of the galaxy luminosity density and cosmic star formation rate by means of detailed chemical evolution models for galaxies of different morphological types, i.e., elliptical, spiral, and irregular, which successfully reproduce the local properties of such galaxies. We match our chemical evolution models with a photometric code that allows us to compute the galaxy spectra and magnitudes when the IMF is fixed. We normalize the galaxy fractions according to the \( B \)-band luminosity function (LF) as measured by Marzke et al. (1998), and we compute the LF in other bands as a function of redshift on the basis of the photometric evolutive corrections and colors predicted by our models. Our detailed study allows us to provide an answer to several questions concerning the cosmological evolution of the baryons in the universe in the form of stars and metals. In particular, we study the cosmic metal production and the related missing-metal problem. This can indicate how the chemical enrichment of the intergalactic medium has occurred and what might be the nature of the objects observed in the high-redshift universe, such as Lyman break galaxies (LBGs) and hyperluminous infrared galaxies. Finally, we focus on the cosmic evolution of Type Ia and II supernova (SN Ia and SN II) rates, and gain further independent probes of how galactic structures have evolved in the universe since their formation. The paper is organized as follows: in § 2 we review the current observational status concerning the luminosity density and the star formation measurements in low- and high-redshift galaxies, in § 3 we describe the theory at the basis of our chemospectrophotometric models, in § 4 we present our results, and in § 5 we draw the conclusions.

2. OBSERVATIONS OF HIGH-REDSHIFT GALAXIES: INTEGRATED LUMINOSITY DENSITY AND COSMIC STAR FORMATION RATE

2.1. Determining the Galaxy Luminosity Function

The total luminosity density (LD) in a given band is the integrated light radiated per unit volume from the entire galaxy population. The distribution of absolute magnitudes for galaxies of any specified Hubble type is represented by the LF (Efstathiou, Ellis, & Peterson 1988; Binggeli, Sandage, & Tammann 1988). The LF is often parameterized according to the form defined by Schechter (1976):

\[
\Phi(L)dL/L^* = \Phi^*(L/L^*)^{-\alpha} \exp(-L/L^*)dL/L^*,
\]

where \( \Phi^* \) is a normalization constant related to the number of luminous galaxies per unit volume, \( L^* \) is a characteristic luminosity, and \( \alpha \) is associated with the slope of the function, which accounts for the percentage of faint systems. The LD stems from the integral over all magnitudes of the observed LF:

\[
\rho_L = \int \Phi(L)(L/L^*)dL.
\]

Different determinations of the local field LF (Loveday et al. 1992; Marzke, Huchra, & Geller 1994a; Ellis et al. 1996; Marzke et al. 1998; Cross et al. 2001) show several discrepancies (Wright 2001), in the sense that all three parameters are not fully constrained by observations (Ellis 1997). Recent progress has been made in the determination of the LF as a function of morphology (Marzke et al. 1994b, 1998; Brinchmann et al. 1998; Kochanek et al. 2001) and of spectral type (Heyl et al. 1997; Madgwick et al. 2002) or color (Blanton et al. 2001), which is important in determining the relative contributions of different galaxy types to the total luminosity density in the local universe. The contribution of different morphological types is a function of the band in which the LF is estimated, with early-type galaxies contributing a substantial fraction of the total emissivity at long wavelengths, namely, in the \( I \) and \( K \) bands, where old massive galaxies dominate (Kochanek et al. 2001), whereas late star-forming spiral galaxies are the major contributors in the \( B \) and \( U \) bands (Marzke et al. 1998; Fukugita, Hogan, & Peebles 1998). Notwithstanding the uncertainties in the LF parameters, there is an overall concordance among various observations regarding the redshift evolution of the galaxy LD. This overall agreement concerns in particular the \( 0 < z < 1 \) redshift range, where the LD is observed to rise sharply, although the precise steepness is still under debate (Cowie, Songaila, & Barger 1999; Lilly, Carollo, & Stockton 2003). On the other hand, the high-redshift trend is rather uncertain, since surface brightness–dimming effects could be significant (Lanzetta et al. 2002) and since the bulk of the available data have been performed in the rest-frame UV, which can be seriously affected by dust obscuration effects. Dust tends to absorb the UV light emitted by young stars and to reradiate it in the IR-submillimeter bands. Moreover, the extent to which the presence of dust contaminates the data is rather uncertain, since galaxies with very different bolometric luminosities can have very similar UV luminosities (Adelberger 2001). Some authors (Connolly et al. 1997; Madau et al. 1998b) claim a broad peak in the UV LD located at \( z > 1 \), followed by a fall at higher redshifts. Other authors observe a rather constant behavior at \( z > 1 \) (Sawicki, Lin, & Yee 1997; Pascaleluela, Lanzetta, & Fernández-Soto 1998), which extends to an uncertain epoch when the first galactic structures formed. In particular, according to the recent Hubble Deep Field data, the constancy of the galaxy LD is observed out to \( z \sim 6 \), as reviewed in Thompson (2003).

2.2. Observed Star Formation Rate Density

The determination of the SFR density is related to the measures of star formation in galaxies, which can be performed by means of various emission processes (Madau 1997; Kennicutt 1998a; Schauerer 1999). All the different measures require the assumption of a universal mass function, which allows the calculation of a multiplicative factor connecting the observed luminosity to the SFR (for a discussion on the conversion factors used in the literature at various wavelengths, see Kennicutt 1998a). The UV luminosity density is dominated by the light emitted by young and massive stars; thus it provides an estimate of the cosmic SFR density. Relevant observations of galaxies in the UV are typically performed at 1500 Å (Madau et al. 1996, 1998b; Steidel et al. 1999; Massaro, Iovino, & Buzzoni 2001), 2000 Å (Treyer et al. 1998), and 2800 Å (Lilly et al. 1996; Sawicki et al. 1997; Connolly et al. 1997; Cowie et al. 1999). Other ways to assess star formation include observations of nebular emission lines such as H\(\alpha \) (Gallaga et al. 1995; Gronwall 1998; Tresse & Maddox 1998; Glazebrook et al. 1999) and O\(\pi \) (Hammer et al. 1997). In all these cases the main source of uncertainty in such determinations is still
represented by interstellar extinction, caused either by the interstellar medium (ISM) of the observed galaxy or by our Galaxy. Star formation activity is likely to take place in highly obscured regions, so reliable extinction corrections are required to have accurate estimates of the SFR density based on observations in the UV band. However, without applying any extinction correction, the possibility that very intense star-forming regions are heavily obscured by dust implies that observations at short wavelengths can provide only lower limits to the actual SFR density. For this reason, the reprocessed mid- and far-infrared (FIR) emission from the dust grains, which are heated by the UV and optical light emitted by the young stars, is a more reliable indicator of star formation activity, and it can be used to estimate the dust amount and SFR with fewer selection effects (Blain et al. 1999; Chary & Elbaz 2001). The FIR studies can, however, be complicated by the multicomponent effects of the dust (warm dust or cirrus; Schaerer 1999) and by the old stars and AGN contributions to the heating of the dust. Observations in the FIR and submillimeter bands include the results by Rowan-Robinson et al. (1997), Hughes et al. (1998), and Flores et al. (1999). More recently, observations in the radio continuum have provided other estimates of the SFR at high redshift (Mobasher et al. 1999; Haarsma et al. 2000). Obviously, the discrepancies seen in the observed evolution of the LD are reflected in the measures of the SFR density, with a globally accepted increasing trend between 2000).

3. CHEMICAL AND PHOTOMETRIC EVOLUTION OF GALAXIES

By means of chemospectrophotometric models of galaxy evolution we aim at reconstructing the history of the luminous matter in the universe. These models allow us to follow in detail the evolution of the abundances of several chemical species, starting from the matter reprocessed by the stars and restored into the ISM through stellar winds and SN explosions. We differentiate the galaxy types into elliptical, spiral disk, and irregular galaxies. We assume that the category of galactic bulges is naturally included in the elliptical galaxies. Our assumption is motivated by the fact that they have very similar features: for instance, both are dominated by old stellar populations and respect the same fundamental plane (Binney & Merrifield 1998). This certainly indicates that they are likely to have a common origin; i.e., both are likely to have formed on very short timescales and a long time ago. Detailed descriptions of the chemical evolution models can be found in Matteucci & Tornambé (1987) and Matteucci (1994) for elliptical galaxies, Chiappini, Matteucci, & Gratton (1997) and Chiappini, Matteucci, & Romano (2001) for spiral galaxies, and Bradamante, Matteucci, & D’Ercole (1998) for irregular galaxies. It is worth noticing that we choose these models with their specific assumptions because they reproduce at best the observed local properties of the various galaxy types. According to our scheme, elliptical galaxies form as the result of the rapid collapse of a homogeneous sphere of primordial gas where star formation is taking place at the same time as the collapse proceeds. Star formation is assumed to halt as the energy of the ISM, heated by stellar winds and SN explosions, balances the binding energy of the gas. At this time a galactic wind occurs, sweeping away almost all the residual gas. Spiral galaxies are assumed to form as a result of two main infall episodes. During the first episode the halo forms and the gas shed by the halo rapidly gathers in the center, yielding the formation of the bulge. During the second episode, a slower infall of external gas forms the disk, with the gas accumulating faster in the inner than in the outer region (“inside-out” scenario; Matteucci & François 1989). The process of disk formation is much longer than the halo and bulge formation, with timescales varying from ~2 Gyr in the inner disk to ~7 Gyr in the solar region and up to 15–20 Gyr in the outer disk. Finally, irregular dwarf galaxies are assumed to assemble from merging of protogalactic small clouds of primordial composition, until a mass of ~6 \times 10^9 \, M_{\odot} is accumulated and to produce stars at a lower rate than spiral galaxies. In the next section, we will present a schematic outline of the equations and physical hypotheses at the basis of the models.

### 3.1. Chemical Evolution Models

Let \( G_i \) be the fractional mass of the element \( i \) in the gas within a galaxy; its temporal evolution is described by the basic equation

\[
\dot{G}_i = -\psi(t)X_i(t) + R_i(t) + (\dot{G}_i)_{\text{inf}} - (\dot{G}_i)_{\text{out}},
\]

where \( G_i(t) = M_i(t)/M_{\text{tot}} \) is the gas mass in the form of an element \( i \) normalized to a total initial mass \( M_{\text{tot}} \). The quantity \( X_i(t) = G_i(t)/G(t) \) represents the abundance in mass of an element \( i \), with the summation over all elements in the gas mixture being equal to unity. The quantity \( G(t) = M_{\text{tot}}(t)/M_{\text{tot}} \) is the total fractional mass of gas present in the galaxy at time \( t \), and \( \psi(t) \) is the instantaneous SFR, namely, the fractional amount of gas turning into stars per unit time. The quantity \( R_i(t) \) represents the returned fraction of matter in the form of an element \( i \) that the stars eject into the ISM through stellar winds and SN explosions; this term contains all the prescriptions regarding the stellar yields and the SN progenitor models. The two terms \( (\dot{G}_i)_{\text{inf}} \) and \( (\dot{G}_i)_{\text{out}} \) account for the infalling external gas from the intergalactic medium and for the outflow, occurring by means of SN-driven galactic winds, respectively. The main feature characterizing a particular morphological galactic type is represented by the prescription adopted for the star formation history, summarized in the SFR expression.

In the case of elliptical galaxies the SFR \( \psi(t) \) (per gigayear) has a simple form and is given by

\[
\psi(t) = \nu G(t).
\]

The quantity \( \nu \) is the efficiency of star formation, namely, the inverse of the typical timescale for star formation. In the case of elliptical galaxies, \( \nu \) is assumed to drop to zero at the onset of a galactic wind, which develops as the thermal energy of the gas heated by SN explosions exceeds the binding energy of the gas (Arimoto & Yoshii 1987; Matteucci & Tornambé 1987). This quantity is strongly influenced by assumptions concerning the presence and distribution of dark matter (Matteucci 1992); for the model adopted here a diffuse \( R_e/R_d = 0.1 \), where \( R_e \) is the effective radius of the galaxy and \( R_d \) is the radius of the dark matter core) but massive \( (M_{\text{dark}}/M_{\text{lum}} = 10) \) dark halo has been assumed. In the case of irregular galaxies we have assumed a continuous star formation rate always expressed as in equation (4) but
characterized by an efficiency lower than the one adopted for elliptical galaxies. In the case of spiral galaxies, the SFR expression (Chiappini et al. 1997) is

\[ \psi(r, t) = \mu \left( \frac{\sigma(r, t)}{\sigma(r_0, t)} \right)^{2(k-1)} \left( \frac{\sigma(r, t_{\text{Gal}})}{\sigma(r, t)} \right)^{k-1} \sigma_{\text{gas}}(r, t), \]

where \( \nu \) is the SF efficiency, \( \sigma(r, t) \) is the surface mass density at a radius \( r \) and time \( t \), \( \sigma(r_0, t) \) is the total surface mass density in the solar region, and \( \sigma_{\text{gas}}(r, t) \) is the surface gas density. For the gas density exponent \( k \) a value of 1.5 has been assumed by Chiappini et al. (1997) to ensure a good fit to the observational constraints at the solar vicinity and to be in agreement with the estimates by Kennicutt (1998b). The three different star formation rates for elliptical, spiral, and irregular galaxies as functions of time and for a Salpeter IMF are shown in Figure 1.

### 3.1. Supernova Rates

The true nature of SNe Ia and their progenitors is currently a matter of debate. Several models have been proposed so far, but they are divided between two main competing scenarios. According to the single-degenerate (SD; Whelan & Iben 1973) scenario, a C–O white dwarf accretes mass from a nondegenerate companion until it reaches the Chandrasekhar mass (~1.4 \( M_\odot \)) and explodes via C deflagration leaving no remnant. The alternative double-degenerate (DD; Iben & Tutukov 1984) model sees the merging of two C–O white dwarfs which, because of the loss of angular momentum via gravitational wave radiation, coalesce and explode by C deflagration. For our purposes we adopt the SD model, which generally best represents the characteristics of the majority of SNe Ia, as discussed in Matteucci & Recchi (2001). SN II explosions are supposed to originate from core collapse of single massive (\( M > 8 M_\odot \)) stars, with maximum masses allowed of 100 \( M_\odot \).

The SN Ia rate is expressed as

\[ R_{\text{Ia}}(t) = A \int_{M_{\text{Bm}}}^{M_{\text{BM}}} \phi(M) \psi(t - \tau_M) dM, \]

where \( A \) is the fraction of binary systems that can end as SNe Ia within the IMF mass range and have a total mass \( M_{\text{Bm}} \leq M \leq M_{\text{BM}}, \) \( \mu = M_2/M_1 \) is the ratio of the secondary component of the binary system (i.e., the less massive one) to the total mass of the system, and \( f(\mu) \) is the distribution function of this ratio. Statistical studies indicate that mass ratios close to 0.5 are preferred, so the formula

\[ f(\mu) = 2^{1+\gamma}(1+\mu)^\gamma \]

is commonly adopted (Matteucci & Recchi 2001), with \( \gamma = 2 \) as a parameter; \( \tau_M \) is the lifetime of the less massive star in the system, which lives longer and therefore determines the timescale for the explosion. The assumed value of \( A \) is \( \sim 0.1. \) This value assures that the present SN rates are reproduced in each galactic type. For the masses \( M_{\text{Bm}} \) and \( M_{\text{BM}} \) we chose the values 3 and 16 \( M_\odot \), respectively (see Matteucci & Greggio 1986). The SN II rate is simply expressed as

\[ R_{\text{II}}(t) = (1 - A) \int_{M_{\text{Bm}}}^{M_{\text{BM}}} \phi(M) \psi(t - \tau_M) dM + \int_{M_{\text{Bm}}}^{M_{\text{BM}}} \phi(M) \psi(t - \tau_M) dM. \]

The IMF has been assumed to be constant in space and time and among galaxies. We have compared results calculated with two different IMFs, i.e., the Salpeter (1955) and the Scalo (1986).

#### 3.2. Spectrophotometric Model

The spectrophotometric calculations have been performed by means of the model by Jimenez et al. (1998). This model is based on the stellar isochrones computed by Jimenez et al. (1998) and the stellar atmospheric models by Kurucz (1992). The main advantage of this photometric code is that it allows one to follow in detail at every single step the metallicity evolution of the gas from which the stars form, at variance with other popular photometric models that require the assumption of a constant metallicity. Using the stellar inputs, first we build simple stellar population (SSP) models consistent with the chemical evolution at any given time and weighted according to the assumed IMF. Then, a composite stellar population consists of the sum of different SSP formed at different times, with a luminosity at an age \( t_0 \) and at a particular wavelength \( \lambda \) given by

\[ L_\lambda(t_0) = \int_0^{t_0} \int_{Z_1}^{Z_2} \psi(t - t_0) L_{\text{SSP},\lambda}(Z, t - t_0) dZ dt, \]

where the luminosity of the SSP can be written as

\[ L_{\text{SSP},\lambda}(Z, t_0 - t) = \int_{M_{\text{min}}}^{M_{\text{max}}} \phi(m) l_\lambda(Z, M, t_0 - t) dM \]

and \( l_\lambda(Z, M, t_0 - t) \) is the luminosity of a star of mass \( M, \)
metallicity $Z$, and age $t - t_0$, $Z_i$ and $Z_f$ are the initial and final metallicities, $M_{\text{min}}$ and $M_{\text{max}}$ are the smallest and largest stellar mass in the population, $\phi(m)$ is the IMF, and $\psi(t)$ is the SFR at time $t$.

4. RESULTS

4.1. Evolution of the Galaxy Luminosity Density

In the $B$-band, at $z = 0$ the LDs for the single galaxy types are simply given by the integral of the LFs observed by Marzke et al. (1998, see eq. [2]). At redshift other than zero we transform the absolute magnitudes by applying the evolutionary corrections, calculated by means of the spectrophotometric code for every galaxy type:

$$M_B(z) = M_B(z = 0) + 2.5 \log \left[ \frac{\int E_{\lambda/1+z}(z) R_B(\lambda) d\lambda}{\int E_{\lambda/1+z}(0) R_B(\lambda) d\lambda} \right],$$

(11)

where $M_B(z = 0)$ and $M_B(z)$ are the absolute blue magnitudes at redshift 0 and $z$, respectively, $E_{\lambda}(z)d\lambda$ is the energy per unit time radiated at the rest-frame wavelength $\lambda$ by the galaxy at redshift $z$, and $R_B(\lambda)$ is the response function of the rest-frame $B$ band. The second term on the right side of equation (11) represents the evolutionary correction, i.e., the difference in absolute magnitude measured in the rest frame of the galaxy at the wavelength of emission (Poggianti 1997). We then calculate the $B$-band LF at redshift $z$ according to

$$\Phi_B(M_B, z) = \Phi_B(M_B(z)),\quad (12)$$

which is equivalent to assuming evolution in luminosity and not in number. This clearly coincides to allow us to assume that the effects of mergers are small at all redshifts. In bands other than $B$ we assume that the LF shape is the same as in the $B$ band, and we calculate the LF in the given band ($X$) by transforming the absolute magnitudes according to the rest-frame galaxy colors as predicted by the spectrophotometric model:

$$M_X = M_B + (X - B)_\text{rf}.\quad (13)$$

Finally, the total luminosity density per unit frequency in a given band $\rho_\lambda$ is given by the sum of the single contributions of the three different galactic morphological types (elliptical, spiral, and irregular):

$$\rho_\lambda(z) = \sum_i \rho_{\lambda,i}(z).\quad (14)$$

Figures 2 and 3 show the predicted evolution of the total LD in the $U$ (centered at 3650 Å), $B$ (centered at 4450 Å), $I$ (centered at 8060 Å), and $K$ (centered at 21900 Å) bands and the contributions of each morphological type for a Salpeter (1955) and a Scalo (1986) IMF, respectively. In all bands, at early times the total LD is dominated by the light produced by elliptical galaxies, which experience their strong starburst, during which they are the most intense sources in each photometric band. After this phase, which lasts $\sim$0.3 Gyr, they will evolve passively for the rest of their life. On the other hand, the disks of spiral galaxies form stars continuously at all epochs: their luminosity increases slowly until 3 Gyr from the beginning of the star formation, where it reaches a broad peak; then it starts to decrease significantly, because of the progressive consumption of their gas reservoirs.

Irregular galaxies are the most slowly evolving systems and their star formation rates never reach the values recorded in spiral disks and elliptical galaxies. As a consequence, their LD values are the smallest at any time in any band.
In the \(I\) and \(K\) bands the difference between the spiral and elliptical luminosity densities are small after 3 Gyr. At this epoch the total amount of stars is nearly in place in both types. At the present time (13 Gyr), the contributions of elliptical and spiral galaxies to the total luminosity density in the \(I\) and \(K\) bands are practically the same, at variance with what happens in the \(B\) and \(U\) bands. The difference between the Salpeter and the Scalo IMF concerns the stars in the high-mass regime (\(M > 8 M_\odot\)), which are more numerous in the former case. This translates into the amount of UV and \(B\) light emitted by all galaxies, which is sensitively larger with the Salpeter than with the Scalo IMF. At longer wavelengths the difference diminishes: in the \(I\) band, where there is still a significant contribution brought by high-intermediate mass stars experiencing the asymptotic giant branch phase, the difference between the elliptical and spiral luminosity is stronger with the Scalo IMF, whereas the \(K\)-band luminosities have practically the same behavior in both cases.

Figure 4 shows the predicted and observed evolution of the LD in various bands for a Salpeter (left) and a Scalo (right) IMF and for a galaxy formation redshift of \(z_f = 5\), having assumed an Einstein–de Sitter (EdS) cosmological model (\(\Omega_\text{m} = 1, \Omega_\Lambda = 0\)) and \(h = 0.5\). Figure 5 shows the same as in Figure 4, but in the case of a lambda cold dark matter cosmology (\(\Lambda\)CDM, \(\Omega_\text{m} = 0.3, \Omega_\Lambda = 0.7\)) and \(h = 0.65\). Figures 6 and 7 show the same as in Figures 4 and 5, respectively, but with a galaxy formation redshift of \(z_f = 10\). The data have been converted from the EdS to the \(\Lambda\)CDM cosmology according to the prescriptions given by Somerville et al. (2001). Given the slight discrepancy between the \(B\)-band LF normalization by Marzke et al. (1998), adopted for our estimate in the local universe, and the one by Ellis et al. (1996), which is shown in the plots, we have renormalized our value at \(z = 0\) to the one by Ellis et al. (1996) to better stress the goodness of our fit.

In the \(U\) band (top) the data show a considerable spread, with large error bars at any redshift. All the UV data reported in the figure are not extinction-corrected, with the only exception of the three points measured by Massarotti et al. (2001). Our predictions indicate a peak in the total UV

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**Fig. 4.** — Top: Predicted (solid line) and observed luminosity densities in the \(U\) band for a Salpeter IMF (left) and Scalo IMF (right) in the case of galaxy formation at \(z_f = 5\). Data are from Pascale, Lanzetta, & Fernández-Soto (1998; 1500 Å; filled hexagons), Steidel et al. (1999; open hexagons), Treager et al. (1998; 2000 Å; cross), Massarotti, Iovino, & Buzzoni (2001; 1500 Å; stars), Madau et al. (1998b; 1500 Å; filled pentagons), Lilly et al. (1996; 2800 Å; filled circles), Connolly et al. (1997; 2800 Å; open squares), and Cowie, Songaila, & Barger (1999; four-pointed stars), with extinction-corrected data from Massarotti et al. (2001; three-pointed stars). Bottom: Predicted and observed luminosity densities in the \(B\), \(I\), and \(K\) bands. Data are from Ellis et al. (1996; 4400 Å, \(B\); open triangles), Lilly et al. (1996; 4400 Å, \(B\); open pentagons), Connolly et al. (1997; 4400 Å, \(B\); filled squares), Lilly et al. (1996; 1 μm \(I\); open circles), and Gardner et al. (1997; 2.2 μm \(K\); filled triangle). The adopted cosmology is the one of Einstein–de Sitter (\(\Omega_\text{m} = 1, \Omega_\Lambda = 0\)) with \(h = 0.5\).
LD corresponding to the redshift of galaxy formation and a monotonically decreasing trend down to $z = 0$, with a particularly strong evolution between $z = 1$ and 0. This last feature is in agreement with the data by Pascarelle et al. (1998) and with the low-redshift value by Treyer et al. (1998). We do not see evidence for the very steep drop observed by Lilly et al. (1996). From Figures 4 and 5 we note that, if the peak generated by elliptical formation were shifted at $z \sim 3$, it would be fairly consistent with the extinction-corrected measures by Massarotti et al. (2001), in particular in the case of the Scalo IMF. To our knowledge, the extinction-corrected data by Massarotti et al. (2001) represent the first observational evidence for a very high peak in the observed UV LD, which could be clearly ascribed to the massive star formation occurring during the formation of spheroids.

In the $B$ band (bottom) there is a smaller number of detections than in the UV but a better agreement between the observations and the predictions in the $0 < z < 1$ redshift range. The smallest number of observations is found in the $I$ and $K$ bands. At $z = 0$ the $K$-band LD is rather well constrained by several measures (Gardner et al. 1997; Loveday 2000; Cole et al. 2001; Kochanek et al. 2001), which show a substantial agreement with one another. For clarity, in our plots we have chosen one single value, the one by Gardner et al. (1997). At redshift larger than zero, in the $I$ band the only observations at our disposal are the ones by Lilly et al. (1996) at 1 $\mu$m. We note that our curves reproduce very well the observed evolution of the LD in the $B$, $I$, and $K$ bands. The best agreement between the data and the predictions is achieved in the case of the $\Lambda$CDM cosmology, especially in the $I$ and $K$ bands. This occurs mainly because, having assumed galaxy formation redshifts of $z_f = 5$ and 10, in the $\Lambda$CDM cosmology a formation redshift of $z_f = 5 (z_f = 10)$ corresponds to a look-back time of 13.26 Gyr (14 Gyr), whereas in the EdS $z_f = 5 (z_f = 10)$ it corresponds to 12.15 Gyr (12.68 Gyr). This means that in the $\Lambda$CDM cosmology galaxies are older than in the EdS; consequently they contain redder stellar populations.

Both the Salpeter and the Scalo IMFs provide satisfactory results. As already mentioned, the Salpeter IMF is richer in high-mass stars than the Scalo IMF.

The consequence of this is that with the Salpeter IMF all galaxies are more luminous at the shortest wavelengths, at which these stars emit the bulk of their light. Moreover, with the Salpeter IMF galaxies are on average redder than with the Scalo one. This translates into slightly higher values of the $I$ and $K$ LDs. However, given the uncertainties and the small data sample in the $I$ and $K$ bands, it is difficult to conclude which choice for the IMF should be preferred.

![Fig. 5.](image_url)
main result is that the disks of spiral galaxies are mainly responsible for the observed decrease of the total LD in the U and B bands between $z_C \sim 1$ and $z_C \sim 0$, whereas in the I band the decline is due to contributions from both spiral and elliptical galaxies, as can be seen also in Figures 2 and 3.

Figures 6 and 7 show the evolution of the comoving LD in various bands, assuming that galaxies formed at $z_f = 10$, having assumed an EdS and $\Lambda$CDM cosmology, respectively, and in the cases of a Salpeter (left) and a Scalo (right) IMF. The predictions are still in fair agreement with the observations, in particular in the $0 < z < 1$ redshift range. The main differences concern the predictions at high redshift: the $z_f = 10$ scenarios allow for a nearly constant LD throughout a wider redshift range. As far as the $z < 1$ behavior of the LD is concerned, little difference can be seen when we assume a global galaxy formation at $z_f = 5$ or 10. This is due to the short cosmic time elapsed between $z = 5$ and 10 both in the EdS and $\Lambda$CDM cosmologies, namely, 0.53 and 0.74 Gyr, respectively. This timescale is much shorter than the one corresponding to the $0 < z < 1$ redshift range, i.e., 8.43 Gyr in the EdS cosmology and 8.31 Gyr in the $\Lambda$CDM cosmology, having thus little influence on what happens during the latter period. The study of the galaxy LD at high redshift is crucial for understanding the epoch of spheroid formation.

Unfortunately, the high-redshift measures concern only the UV band, which is the most seriously affected by dust extinction effects (Adelberger & Steidel 2000). If the attenuation by dust is as serious as advocated by Massarotti et al. (2001), the peak generated by the formation of massive spheroids could lie anywhere in the $z > 1$ region, but it would be hidden if the associated strong starbursts occurred in sites heavily obscured by dust. In fact, spheroids are the systems that most rapidly reach oversolar metallicities (Pettini et al. 2002; Matteucci & Pipino 2002); therefore the formation of dust grains could be particularly favored if, as it is reasonable to assume, the probability of dust formation is proportional to the metal content.

High-redshift observations at longer wavelengths, i.e., in bands not affected by biases caused by dust extinction, could provide fundamental hints about the epoch of major spheroid formation, as well as high-redshift observations in the FIR/submillimeter bands, where dust reemits all the starlight absorbed in the rest-frame $B$ and $U$ bands (Hughes et al. 1998; Blain et al. 1999).

4.2. Cosmic Star Formation Rate Density

Figure 8 shows the evolution of the cosmic SFR density as a function of redshift (Madau’s plot) as predicted by our models and as observed by several authors in the case of a
CDM cosmology and galaxy formation at $z_f = 5$. The cosmic SFR density is not a directly observed quantity: to be evaluated it needs, besides the measure of the LD at certain wavelengths (mostly 1500 and 2000 Å), the adoption of a universal IMF to calculate the conversion factor between the observed $\rho_\beta$ and $\rho_\star$. For this reason the determination of this quantity is affected by two main sources of uncertainty. One is related to the determination of the calibration constant, which is uncertain if the universal IMF is varying throughout cosmic time. The second is related to the dust extinction affecting the UV observations.

We have computed the cosmic SFR density according to

$$\rho_\star(z) = \sum_i \rho_{\beta i}(z) \left( \frac{M}{L_{\beta i}} \right) (z) \psi_i(z) ,$$

(15)

where $\rho_{\beta i}$, $M/L_{\beta i}$, and $\psi_i$ are the $B$ LD, the $B$ mass-to-light ratio, and the star formation rate for the galaxies of the $i$th morphological type, respectively. The points in Figure 8 represent estimates based on observations at short wavelengths, except the solid hexagon, which was obtained by means of submillimeter measures by Hughes et al. (1998). However, since the extent of the attenuation by dust is highly uncertain (see Steidel et al. 1999; Hopkins et al. 2001a; Thompson, Weymann, & Storrie-Lombardi 2001), we have chosen to use the data uncorrected for dust extinction.
extinction. For this reason, all the data based on optical observations should be regarded as lower limits to the true values. The thick lines in the curves indicate lower and upper limits on the SFR density calculated by Haarsma et al. (2000) from radio observations. As well as the point from submillimeter data, these estimates need no correction for dust obscuration since the radio emission at \( \nu > 1 \text{ GHz} \) passes freely through dust.

At \( z \sim 0 \) we overpredict the value observed by Gallego et al. (1995) by a factor of 4. Interestingly, our estimate is instead in very good agreement with a recent determination based on Local Group observations by Hopkins, Irwin, & Connolly (2001b), which calculate a local SFR density higher than the one by Gallego et al. (1995) by a factor of \( \sim 5 \). This fact implies that, even in the local universe, dust obscuration could introduce serious biases in the determinations of the global SFR density. Since the probability of intercepting dusty objects increases in lockstep with the line of sight, it is conceivable that this effect could become more and more pronounced at increasing redshift. Another source of discrepancy between our local value and the one by Gallego et al. (1995) is the normalization of the luminosity density that we have chosen, which in this case seems too high. Since the discrepancy between our local value and the observed one arises from the combination of both effects, it seems very difficult to quantify the uncertainty associated with the choice of the normalization. If we were to neglect all the effects due to dust obscuration and if we took the value by Gallego et al. (1995) at face value, the uncertainty due to the normalization would be of a factor of 4. In Figure 8, to better stress the comparison between our prediction and the observations, our curve has been renormalized to the value by Gallego et al. (1995). Our predictions indicate a peak in the SFR density at high redshift due to massive star formation in spheroids. In our models, the SFR in elliptical galaxies can reach very high values (up to \( 1000 \, M_\odot \, \text{yr}^{-1} \)), very similar to the ones observed in some SCUBA (Ivison et al. 2000) and hyperluminous infrared galaxies (Rowan-Robinson et al. 1997, 2000). Such values are motivated by the fact that, to reproduce several observational features such as the observed increase of the \([\text{Mg}/\text{Fe}]\) ratio and the velocity dispersion \( \sigma \), giant elliptical galaxies, i.e., with masses on the order of \( \sim 10^{11} \, M_\odot \), have to form all their stars on very short timescales, i.e., \( \tau \lesssim 1 \, \text{ Gyr} \) (Matteucci 1994). Hence, the possible SFRs for high-mass elliptical galaxies span the range \( \sim 100-1000 \, M_\odot \, \text{yr}^{-1} \). If we were to assume a galaxy of \( M \sim 10^{10} \, M_\odot \) as a typical elliptical galaxy, with a star formation timescale of \( \sim 1 \, \text{ Gyr} \), this would lower the peak in the SFR density by a factor of 10. As already mentioned in § 4.1, if most of the star formation in the universe occurred at very high redshift and in sites highly obscured by dust, there could be a peak somewhere at \( z > 1 \), which would remain completely unseen in the observed \( \rho_\star - z \) plot.

4.3. Evolution of the Stellar Mass Density

Figure 9 shows the predicted and observed evolution of \( \Omega_\star \), namely, the stellar mass density (living stars plus remnants) divided by the critical density of the universe. The stellar mass density is given by

\[
\rho_\star(z) = \sum_i \rho_{Bi}(z) \left( \frac{M}{L_{Bi}} \right)_{Bi}(z),
\]

where \( \rho_{Bi}(z) \) is the \( B \) luminosity density and \( M/L_{Bi} \) is the \( B \) mass-to-light ratio for the galaxy of the \( i \)th morphological type. In Figure 9 we show two values of the total stellar mass density measured in the local universe: the one by Cole et al. (2001), valid for the whole galaxy population, and the one by Pérez-González et al. (2003), representing the contribution brought by local star-forming galaxies. The discrepancy between our results and the observations (and among the observations) at \( z = 0 \) is likely to be ascribed to uncertainties in the normalization chosen for the local LF. We note that our prediction for the total stellar mass density is consistent with the values by Brinchmann & Ellis (2000) and with the low-redshift value by Dickinson et al. (2003).

In our scenario, elliptical galaxies build up the totality of their stellar mass at very early times, whereas disks of spiral galaxies and irregular galaxies build up their stars progressively. Thus, the rise in the \( 3 \geq z \geq 0.5 \) redshift range, observed by Dickinson et al. (2003), is mainly determined by spiral galaxies, namely, by the same galaxies contributing to the drop in the cosmic SFR density between \( z \sim 1 \) and \( z = 0 \). Finally, it is worth noting that our \( z = 0 \) mass density values are in good agreement with the estimates by Fukugita et al. (1998) for spheroids, disks, and irregular galaxies.

4.4. Missing-Metal Crisis

The metals in the high-redshift universe are observed in various amounts in different sites. One is represented by the DLA systems, which are considered to be the high-redshift counterparts of the gas-rich galaxies in the local universe and
are usually associated with slowly evolving galactic or sub-galactic systems (Pettini et al. 1999; Prochaska & Wolfe 1999; Calura, Matteucci, & Vladilo 2003). Other sites of significant metal production at high redshift are the LBGs (Steidel et al. 1996, 1999), whose high metal abundances, strong luminosities, and kinematical features indicate their possible association with star-forming spheroids (Matteucci & Pipino 2002; Pettini et al. 2002). A certain amount of the metals produced in protogalaxies is ejected through SN-driven winds into the intergalactic medium, whose presence is detected as a forest of absorption lines blueward of the Lyα emission lines of high-redshift QSOs (for a review of the argument, see Pettini 2000; Bechtold 2003). The intergalactic gas is highly ionized and is likely to account for most of the baryons at low and high redshift. In this medium the lowest metallicity in the universe can be observed (Songaila 2001), possibly due to enrichment by Population III stars (Ostriker & Gnedin 1996). Finally, an uncertain amount of metals is locked up in QSOs and active galactic nuclei (Hamann 1997), objects with metallicities even higher than the ones observed in LBGs (Matteucci & Padovani 1993). We evaluate the metal ejection rate (MER) density according to Pagel (2002) by assuming the proportionality between the comoving density of metals and the cosmic SN rate (Madau et al. 1996; Pettini 1999; Pagel 2002).

This is in principle a rough approximation, since it is equivalent to ignoring the contribution of SNe Ia and considering only the elements produced explosively by massive stars. However, for our purposes this assumption is reasonable since the main contributor to the total metallicity Z is the oxygen, which is produced on very short timescales exclusively by massive stars. A more refined calculation of the production rate in the universe of various elements will be the object of a forthcoming paper (F. Calura & F. Matteucci 2003, in preparation).

If we integrate the predicted MER density across the epoch ranging from 13.3 to 11 Gyr, which for the ΛCDM cosmology corresponds to the redshift range in which the bulk of DAL systems and LBGs are found, we obtain

\[
\int_{11 \text{ Gyr}}^{13.3 \text{ Gyr}} \rho z(t) dt = 5.2 \times 10^6 \, M_\odot \, \text{Mpc}^{-3}.
\]  

An approximate estimate based on the observed values of \(\rho_8\) yields \(5 \times 10^6 \, M_\odot \, \text{Mpc}^{-3}\) (Pagel 2002), a value in excellent agreement with our appraisal, though slightly lower. The observed contribution from DAL systems and LBGs represents \(\sim 10\%\) of the estimate by Pagel and us. We find such a high value for the total metal density at high redshift since we assume that all elliptical galaxies form at the same time. If we spread the formation of elliptical galaxies over a wide redshift range, we would probably find a lower value both for the SFR density peak and for the metal density. For this reason, the values predicted for such peak and for the total amount of missing metals at high redshift should be regarded as upper limits. However, this does not mean that the missing-metal crisis could not be even more serious than the observations indicate if most of the metals were produced in dust-obscured starbursts associated with early spheroid formation. We suggest that, irrespective of the amount of metals, the most plausible site of the missing metals could be the warm gas in galaxy groups and protoclusters, in which the metals could have been ejected through strong winds following the intense starbursts in elliptical galaxies. In such an environment, the presence of diffuse metals could be difficult to detect, likely because of virial temperatures lower than the ones observed in clusters (Renzini 1997; Fukugita et al. 1998). The main sources of strong winds could be the LBGs, where recent kinematic studies have indicated the frequent presence of strong largescale outflows (Pettini et al. 2001, 2002). Another possible source is represented by the SCUBA (Blain et al. 1999; Trentham, Blain, & Goldader 1999) and hyperluminous infrared galaxies (Rowan-Robinson 2000), very luminous in the infrared band but faint in the optical, where the most intense observed starbursts are likely to occur and which are natural candidates for massive protocore elliptical galaxies (Ivison et al. 2000).

### 4.5. Cosmic SN Rate

Another key issue in the study of galaxy evolution is the determination of the cosmic SN rate, which can provide useful constraints on the cosmological parameters (Marri, Ferrara & Pozzetti 2000), on the possible SN progenitor models, and on the evolution of the cosmic star formation history. The observed cosmic SN rate is expressed in SNu, i.e., in SNe per unit time per unit blue luminosity:

\[ 1 \, \text{SNu} = 1 \, \text{SN} / 10^{10} \, L_\odot / \text{B} \text{ per century.} \]  

The observed SN rate \(R\) is expressed as

\[ R = N / S \]  

(Hardin et al. 2000), where \(N\) is the number of SNe detected and \(S\) is a sum over the observed galaxies weighted by their blue luminosities \(L_i\):

\[ S = \sum_i L_i \int_{-\infty}^{\infty} \epsilon_i(t, z_i) dt, \]

where \(\epsilon\) is the efficiency to detect in the \(i\)th galaxy a SN whose maximum occurs at time \(t\) in the SN rest frame. For simplicity, we calculate the cosmic SN rate at redshift \(z\) as

\[ R_c(z) = \frac{\sum_i r_i(z)}{\sum_i L_B(z)}, \]

where \(r_i(z)\) represents the number of SNe per 100 yr exploding in the \(i\)th galaxy type at redshift \(z\), whereas \(L_B\) is the predicted blue luminosity of the \(i\)th galaxy type at redshift \(z\). Figures 10 and 11 show the results of our computation of the cosmic SN Ia and SN II rates, calculated in SNu, having assumed a ΛCDM model world and galaxy formation occurring at \(z_f = 5\). In Figure 10 we adopt a universal Salpeter IMF, whereas in Figure 11 a Scalo IMF. We compare our predictions for galaxies of different morphologies with data observed by several authors up to \(z \sim 0.55\) (see Figs. 10 and 11 legends for details). According to our calculations, in the local universe the bulk of SNe Ia explode in elliptical and spiral galaxies. At increasing redshift the contribution of elliptical galaxies becomes more and more significant. At \(z \sim 0\), practically all SNe Ia explode in spiral galaxies, with a small contribution brought by irregular galaxies. In elliptical galaxies SNe II explode only at high redshift because these galaxies are assumed to evolve passively since the interruption of the star formation at the onset of the galactic wind, which occurs at early times. We note that our fit to the observed points is excellent in the case...
of the Salpeter IMF for both SNe Ia and SNe II. In the case of the Scalo IMF we underestimate the number of SNe II in the local universe and we slightly underpredict the SN Ia rate observed at high redshift (\(z/0.55;\) Pain et al. 2002). We stress that, unlike all our previous predictions, the calculation of the SN rate is independent of the luminosity function and is directly comparable to the observations without requiring a normalization at \(z = 0.\) For this reason, the calculation of the SN rate can be considered a very reliable test of consistency for our chemospectrophotometric model. If the cosmic SN rate can be considered a reliable indicator of how star formation has evolved in the universe since the growth of galactic structures, as discussed in Madau, Della Valle, & Panagia (1998a) and Sadat et al. (1998), our result is further evidence that the bulk of the galaxy population have evolved in luminosity and not in number since early times, i.e., that the bulk of the galaxies as we see them today were already in place at early epochs. Observations of the cosmic SN rate at very high redshifts, which we hope will be achievable after the launch of the Next Generation Space Telescope, can provide fundamental clues about the galaxy formation epoch.

5. CONCLUSIONS

In this paper we have used detailed chemospectrophotometric models for galaxies of different morphological types, namely, elliptical, spiral, and irregular, to study the evolution of the galaxy luminosity density in various bands, the cosmic SFR density, and the cosmic SN rate. We have studied the evolution of the baryonic matter in the universe in the form of stars and metals, starting from the \(B\)-band luminosity function observed in the local universe by Marzke et al. (1998), having assumed that the whole galaxy population started forming stars at high redshift. We have considered two different forms for the universal IMF, namely, the Salpeter (1955) and the Scalo (1986), and we have computed our models for different cosmologies, i.e., the Einstein–de Sitter and the \(\Lambda\)CDM. We have compared our predictions with an updated large set of high-redshift observations, and we found an overall good agreement between our predictions and all the observational evidence considered in the present work. In particular, our main results are the following:

1. We reproduce the evolution of the galaxy luminosity density in the \(B, I,\) and \(K\) bands, considering that all galaxy types evolve in luminosity and not in number since the epoch of their formation. Generally, we overestimate the luminosity density observed in the UV, in particular at high redshift. In our scheme, elliptical galaxies suffer high-redshift starbursts after which they evolve as passive systems, i.e., without star formation, whereas spiral disks and irregular galaxies form stars continuously down to the present epoch. At high (> 2) redshift, elliptical galaxies dominate the total emissivity in any optical band. We predict a high-redshift peak generated by the intense starburst in elliptical galaxies that is not visible in the available observations at short wavelengths not corrected by extinction. The cause could be a heavy attenuation by interstellar dust that could hide the most intense star-forming sites or the bulk of the rest-frame UV light emitted by single objects. On the other hand, extinction-corrected high-redshift measurements of the UV flux density (Massarotti et al. 2001) are fully compatible with our predictions. High-redshift observations in bands less sensitive to dust attenuation, currently absent, would be fundamental in probing the existence of such a peak. At \(z < 2,\) in the \(U\) and \(B\) bands the disks of spiral galaxies emit the bulk of the light and are the main contributors to the decline in the galaxy luminosity density observed between \(z \sim 1\) and \(z = 0,\) whereas in the \(I\) and \(K\) bands the light emitted by stars in elliptical galaxies is
comparable to that emitted by the spiral galaxies. Irregular galaxies bring a negligible contribution to the total luminosity density at any epoch and in any band. Both the Salpeter and Scalo IMFs provide very satisfactory results, especially assuming a $\Lambda$CDM cosmological model.

2. We predict that spiral disks are the most active star-forming sites in the universe throughout the redshift interval $0 < z < 1$ which, for a standard $\Lambda$CDM cosmology and $h = 0.65$, corresponds to 57% of the cosmic time. Furthermore, if the SFRs recorded in SCUBA and hyperluminous infrared galaxies can be considered typical for starbursting prototriangular galaxies, we predict a very high peak (up to $\sim 1000$ times the value observed in the local universe) in the cosmic SFR density occurring at the epoch when the bulk of the spheroids formed.

3. According to our calculations, the missing-metal crisis could be even more serious than that proposed by previous authors (Pettini 1999; Pagel 2002) if the bulk of the metals were produced in dust-obscured starbursts associated with an early spheroid formation. We suggest that, regardless of the amount of metals, the most plausible site for the missing metals could be the warm gas in galaxy groups and protoclusters, in which the metals could have been ejected through strong winds following intense starbursts. In such an environment, the presence of the metals would be difficult to detect because of the low virial temperatures. In principle, it could be possible to detect these metals by identifying the most recently assembled clusters of galaxies, provided that they have formed from groups where the missing metals lie. The main sources of such strong winds could be Lyman break (Pettini et al. 2002), SCUBA (Trentham et al. 1999), and hyperluminous infrared galaxies (Rowan-Robinson 2000), which are the best candidates for the high-redshift counterparts of the nearby massive elliptical galaxies.

4. The study of the cosmic SN rate is a fundamental test of consistency for our models since it is completely independent of the normalization of the galaxy population at $z = 0$, which was required by all our previous calculations. We reproduce very well the observed cosmic SN rate, assuming a universal Salpeter-like IMF. The assumption of a Salo IMF causes an underestimate of the local SN II rate and of the SN Ia rate observed at high redshift. We predict that most of the SNe Ia explode in elliptical galaxies at all ages, whereas all the SNe II explode in spiral disks and irregular galaxies after the halt of star formation in elliptical galaxies occurred at high redshift. This is in fair agreement with all our previous results, which indicate that spiral galaxies are the most active star-forming objects since at least $z \sim 1$. Also the observed cosmic SN rate can be explained by assuming a scenario of coeval galaxies whose number is conserved and which evolve purely in luminosity. The determination of the cosmic SN rate at redshifts less than 0.55 (i.e., the highest explored by current SN surveys; Pain et al. 2002), which we hope will be achievable after the launch of the Next Generation Space Telescope, can provide further constraints on galaxy evolution models. All the results obtained in this paper clearly indicate that the bulk of galaxies were already in place at early epochs. According to several recent observations, the presence of high-mass galaxies at high redshift is not rare (Saracco et al. 2003; Ruis et al. 2003; Pozzetti et al. 2003). Furthermore, in the last few years increasing evidence has been found that most (up to 70%) of the extremely red objects discovered in deep NIR and optical surveys could be high-redshift elliptical galaxies (Daddi, Cimatti, & Renzini 2000 and references therein). Certainly, all these evidences seem difficult to reconcile with galaxy formation scenarios in which the bulk of the stellar mass forms at $z < 1$.

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REFERENCES

Adelberger, K. L. 2001, in Starburst Galaxies: Near and Far, ed. L. Tacconi & D. Lutz (Berlin: Springer-Verlag)

Adelberger, K. L., & Steidel, C. C. 2000, ApJ, 544, 218

Arimoto, N., & Yoshii, Y. 1987, A&A, 173, 23

Ascasibar, Y., Yepes, G., Gottloeber, S., & Mueller, V. 2002, A&A, 387, 396

Baugh, C. M., Cole, S., Frenk, C. S., & Lacey, C. G. 1998, ApJ, 498, 504

Bechtold, J. 2003, in Galaxies at High Redshift, ed. J. Pérez-Fournon, et al. (Cambridge: Cambridge Univ. Press), 131

Binggeli, B., Sandage, A., & Tammann, G. A. 1988, ARA&A, 26, 509

Binney, J., & Merrifield, M. 1998, Galactic Astronomy (Princeton: Princeton Univ. Press)

Blain, A. W., Smail, I., Ivison, R. J., & Kneib, J. P. 1999, MNRAS, 302, 632

Blanton, M. R., et al. 2001, AJ, 121, 2358

Boselli, A., Gavazzi, G., Donas, J., & Scodeggio, M. 2001, AJ, 121, 753

Bradamante, F., Matteucci, F., & D’Ercole, A. 1998, A&A, 337, 338

Brinchmann, J., & Ellis, R. S. 2000, ApJ, 536, L77

Bruzual, G., & Charlot, S. 1993, ApJ, 405, 538

Calura, F., & Matteucci, F. 2003, MNRAS, submitted

Calura, F., Matteucci, F., & Vladoilo, G. 2003, MNRAS, 340, 59

Cappellaro, E., Evans, R., & Turatto, M. 1999, A&A, 351, 459

Chary, R., & Elbaz, D. 2001, ApJ, 556, 562

Chiappini, C., Matteucci, F., & Gratton, R. 1997, ApJ, 477, 765

Chiappini, C., Matteucci, F., & Romano, D. 2001, ApJ, 554, 1044

Cole, S., Lacey, C. G., Baugh, C. M., & Frenk, C. S. 2000, MNRAS, 319, 168

Coles, S., et al. 2001, MNRAS, 326, 255

Connolly, A. J., Szalay, A. S., Dickinson, M. E., SubbaRao, M. U., & Brunner, R. J. 1997, ApJ, 468, L11

Cowie, L., Songaila, A., & Barger, A. 1999, AJ, 118, 603

Cross, N., et al. 2001, ApJ, 556, 825

Daddi, E., Cimatti, A., & Renzini, A. 2000, A&A, 362, L45

Dickinson, M., Papovich, C., Ferguson, H. C., & Baudavári, T. 2003, ApJ, 587, 25

Efstathiou, G., Ellis, R., & Peterson, B. A. 1988, MNRAS, 232, 431

Ellis, R. S. 1997, ARA&A, 35, 389

Ellis, R. S., Colless, M., Broadhurst, T., Heyl, J., & Glazebrook, K. 1996, MNRAS, 280, 235

Fall, S. M., Charlot, S., & Pei, Y. 1996, ApJ, 464, L43

Flores, H., et al. 1999, ApJ, 517, 148

Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, ApJ, 503, 518

Gallego, J., Zamorano, J., Aragon-Salamanca, A., & Rego, M. 1995, ApJ, 455, L1

Gardner, J. P., Sharples, R. M., Frenk, C. S., & Carrasco, B. E. 1997, ApJ, 480, L99

Glazebrook, K., Blake, C., Economou, F., Lilly, S., & Colless, M. 1999, MNRAS, 306, 843

Gronwall, C. 1998, in After the Dark Ages: When Galaxies Were Young: The Universe at $z < 5$, ed. S. Holt & E. Smith (New York: AIP), 333

Haarsma, D., Purkis, R., Partridge, R. B., Windhorst, R. A., & Richards, E. A. 2000, ApJ, 544, 641

Hamann, F. 1997, ApJS, 109, 279

Hammer, F., et al. 1997, ApJ, 481, 49

Hardin, D., et al. 2000, A&A, 362, 419

Heyl, J., Colless, M., Ellis, R. S., & Broadhurst, T. 1997, MNRAS, 285, 613

Hopkins, A. M., Connolly, A. J., Haarsma, D. B., & Cram, L. E. 2001a, AJ, 122, 288

Hopkins, A. M., Irwin, M. J., & Connolly, A. J. 2001b, ApJ, 558, L31

Hughes, D., et al. 1998, Nature, 394, 241
