The star formation history as a function of type: constraints from galaxy counts

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Abstract. Deep galaxy counts are among the best constraints on the cosmic star formation history (SFH) of galaxies. Using various tracers, the evolution of the star formation activity may now be followed on a wide range of redshifts ($0 \leq z \leq 4$) covering most of the history of the Universe. Two incompatible interpretations of the observations are currently competing. After applying star formation rate (SFR) conversion factors to the CFRS, H$\alpha$ or ISO samples, many authors conclude to a strong increase ($\simeq$ a factor 10) of the SFR from $z = 0$ to $z = 1$. They also find some evidence for a peak at $z \simeq 1$ and for a rapid decrease at higher redshifts. On the other side, the Hawaii deep surveys favor only a mild increase between $z = 0$ and 1 (Cowie et al., 1996, 1999).

In this paper, we tackle this problem from the point of view of the modelist of the spectral evolution of galaxies. To understand the reason for these discrepant interpretations, we consider three classes of galaxies: E/S0 (“early-type”); Sa–Sbc (“intermediate-type”); Sc–Sd, irregulars and bursting dwarfs (“late-type”). We use the new version of our evolutionary synthesis code, Pégase (Fioc and Rocca-Volmerange, 2000, in preparation), which takes into account metallicity and dust effects. The main results are: i) Late-type galaxies contribute significantly to the local SFR, especially bursting dwarfs (Fioc and Rocca-Volmerange, 1999). Because of that, the cosmic SFR can not decrease by a factor 10 from $z = 0$ to 1. This is in agreement with Cowie et al., 1999’s result. ii) The SFR of intermediate-type galaxies has strongly decreased since $z = 1$. Though the decrease is less than what find Lilly et al., 1996, this suggests that the CFRS and H$\alpha$ surveys are dominated by such bright early spirals. The limits in surface brightness and magnitudes of the observed samples may be the main reason for this selection. iii) The contribution of early-type galaxies increases rapidly from $z = 1$ to their redshift of formation ($\geq 2-3$ for cosmological reasons). Their intense star formation rates at high-$z$ give strong constraints on early ionization phases, primeval populations or metal enrichments.

Keywords: star formation, galaxies, evolution, cosmology

1. Introduction

Long before the supernovae were used to explore the distant Universe, faint galaxy counts were known to be very sensitive to the cosmological parameters and to the redshift of formation. Robust conclusions were derived on the inconsistency with the data of a deceleration parameter

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$\Omega_0 = 0.5$ and a null cosmological constant (Yoshii and Peterson, 1991; Koo, 1990; Guiderdoni and Rocca-Volmerange, 1990). A flat universe $\Omega_0 = 1$ could be saved only by either invoking a non-zero cosmological constant $\Lambda_0$ (Fukugita et al., 1990) or by number evolution (Rocca-Volmerange and Guiderdoni, 1990). No plausible change in star formation parameters might alter these conclusions. So that we adopt hereafter the best values of the cosmological parameters for our analysis of the cosmic star formation rate (SFR) in the Universe, leaving to further studies, the sensitivity of results to this choice.

A large variety of redshift and photometric surveys have been used to trace the SFH. Between $0 \leq z \leq 1$, a ten-fold increase of the SFR (Madau et al., 1996) has been derived from the Canada-France Redshift Survey (CFRS, Lilly et al., 1996) from rest-frame 2800 Å computed by interpolation or, at low-$z$, extrapolation of observed optical and near-infrared data. Similar results were claimed using the Hα surveys (Gallego et al., 1995, Tresse et al., 1998) and the ISO/CFRS data (Flores et al., 1998). On the other hand, the complete redshift and photometric (from U’ to K bands) surveys of galaxies observed by Cowie et al., 1996, 1999 conclude to a milder evolution $SFR \propto (1+z)^{1.5}$ on the same range of redshift and to a higher local SFR, in agreement with the results of the FOCA2000 $z$-survey (Treyer et al. 1998; Sullivan et al. 1999).

Multiwavelength galaxy counts might help to solve this controversy. Interpretations of faint galaxy counts were recently proposed by Pozzetti et al., (1998) and, using the spectral evolution model PÉGASE, by Fioc & Rocca-Volmerange (1999a). The latter notably identified a significant population of bursting dwarf galaxies in the FOCA 2000Å photometric survey (Armand & Milliard, 1994), whose contribution in the optical and near-infrared is however much smaller than that due to the bulk of normal galaxies. In the optical-NIR domain, galaxy counts are attributed to various populations of the Hubble sequence, distributed according to the observed local luminosity functions by spectral types (Marzke et al, 1994, Heyl et al, 1997). Each evolution scenario, mainly constrained by local and low $z$ observations, corresponds to a star formation law. The 9 types computed are hereafter gathered in three groups: Ellipticals-S0, spirals Sa-Sbc, Sc-Irr-dwarfs. In the following we shortly recall the evolutionary modeling of galaxy counts with PÉGASE. Then we present the global SFH with a flat increase for $0 \leq z \leq 1$, lightly shallower that Cowie’s et al., 1999. At higher redshifts, the evolution of elliptical and spiral SFHs is followed on the large $1 \leq z \leq 4$ domain, with different tendencies for the two groups.
2. Modeling faint galaxy counts

2.1. The new version of Pégase

The new version of the spectrophotometric model Pégase (Fioc and Rocca-Volmerange, 1997, 2000 in preparation) follows the evolution of the stellar energy distributions (SEDs) for 9 spectral types ranging from ellipticals to starbursts. The main input data are the stellar evolutionary tracks from the Padova group (Bressan et al., 1994) and the stellar spectra from Kurucz 1995 corrected by Lejeune et al., 1997. Exchanges with the interstellar medium (supernovae ejecta, stellar winds, gas inflow or outflow) are taken into account and allow to follow the evolution of the metallicity of the interstellar medium (ISM) and the stellar populations, as well as the dust opacity. The extinction is computed by a radiative transfer code in various geometries corresponding to the morphological type and for a standard model of grains (Draine & Lee, 1984). In disk galaxies, the stars and the dust are distributed homogeneously in a slab, while in bulges, stars and dust follow a King-like profile (Fioc and Rocca-Volmerange, 1997). The amount of dust is computed from the mass of metals in the ISM. In the most conservative way, star formation rates are proportional to the current gas content, with a type-dependent timescale. This timescale, as well as the e-folding time for infall, are estimated by fitting the synthetic spectra to \( z = 0 \) observational template spectra and colors. To this purpose, statistical optical-to-near infrared colors were recently determined as a function of type, luminosity and inclination from a catalog of magnitudes corrected for aperture effects (Fioc and Rocca-Volmerange, 1999b).

2.2. Other inputs and results

The type-dependent \( z = 0 \) luminosity functions of galaxies are from the Autofib Redshift Survey (Heyl et al., 1997). The adopted cosmological parameters in the classical formalism of Friedmann and Lemaître are \( H_0 = 65 \text{ km.s}^{-1}.\text{Mpc}^{-1} \), while \( \Omega_0 \) and \( \Lambda_0 \) belong to the \([0,1]\) interval. Our two preferred sets of values of \((\Omega_0; \Lambda_0)\) are \((0.1; 0)\) and \((0.3; 0.7)\).

Predicted multiwavelength galaxy counts \( N(m) \) and redshift distributions \( N(z) \) are plotted on Figures 1 and 2 for pure luminosity evolution models and are compared to the observations. The most constraining data on the cosmology are the faint counts from the Hubble Deep Field (Williams et al., 1996).

\(^1\) The codes are accessible on the WEB at http://www.iap.fr/users/fioc or rocca or by anonymous ftp at ftp.iap.fr in the directory /pub/from_users/pegase
Figure 1. Predicted galaxy count in $b_J$, $U$, $F300W_{AB}$, $I$ and $K$ compared to the observations and normalized to them at $b_J = 16$. The luminosity function is from Heyl et al., 1997. The adopted cosmology corresponds to $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0 = 0.3$ and $\Lambda_0 = 0.7$. The dashed line is the case without evolution.

Because of the relation between $z$ and $t$, redshift distributions rather put constraints on the SFH, especially the Hawaii surveys (Cowie et al., 1996, 1999). The CFRS sample, complete till $I_{AB} = 22.5$ is well reproduced by our models (Figure 2, top). However, our SFH does not show the rapid evolution found by Lilly et al. (1996) from the same data, which is puzzling. Figure 2, bottom, highlights the two populations of blue galaxies ($B-I < 1.6$) observed in the Hawaii galaxy survey by Cowie et al. (1996) and in general in faint counts. The nearby blue population is sufficiently faint ($22.5 \leq B \leq 24$) to be assimilated to a population of dwarfs, undetectable at higher redshifts while the faint distant blue population ($z > 1$) is also detected in the deepest photometric surveys as the HDF-N.
Figure 2. **Top:** The redshift distribution $N(z)$ from the CFRS fitted with our evolution model PÉGASE. The adopted cosmology corresponds to $H_0 = 65 \text{km.s}^{-1}.\text{Mpc}^{-1}$, $\Omega_0 = 0.3$ and $\Lambda_0 = 0.7$. Dashed line is the case without evolution.

**Bottom:** The redshift distribution of very faint objects from the Hawaii deep survey (Cowie et al., 1996) are fitted with our model PÉGASE. Cosmological parameters are the same as above. The grey zone identify the bluest (B-I < 1.6) populations observed at low and high redshifts and the thick line is the corresponding prediction.
3. Star formation histories

For each galaxy type, the star formation law (rate and initial mass function) determines the spectral evolution. Cosmological and evolutionary corrections may then be derived from the synthetic spectra and be applied to the local type-dependent luminosity functions to compute more distant ones and to predict galaxy counts. The interest of this procedure is that the models can be compared directly to the observations, without the inconsistencies brought by the use of different conversion factors, depending on the wavelength and the redshift.

Figure 3 shows the global SFH and the contributions of the three groups. The main results are the slow evolution of the global SFH ($SFH \propto (1+z)^{1.2}$), close to Cowie et al., 1999’s result, and the six-fold decrease of the SFR of evolved spirals from $z = 1$ to 0. No peak is predicted at $z \approx 1$. The maximal SFR actually occurs just after the formation of E and S0 galaxies, at a redshift $z_{for} \approx 10$ on Figure 3. A similar result (with sharper slopes) would be obtained with $z_{for} = 4$; such low value is however in worse agreement with the data than $z_{for} = 10$ (Rocca-Volmerange and Fioc, 1999). Yet, the SFR of spiral galaxies flattens at $z > 2$. At such high $z$, results are much more sensitive to cosmology and evolution scenarios than for $z \leq 1$. In particular, the global SFR might follow a similar trend if E/S0 galaxies formed by merging rather than by monolithic collapse.

The examination of the SFH of the various types may help to solve the contradiction between the “Madau” diagram and Cowie et al.’s results. Each galaxy group has a different contribution to the global SFH, which must be analyzed separately:
i) The late-type group dominates the SFR at \( z = 0 \) (70\%) but its weight rapidly decreases at \( z > 1 \). Many of these galaxies are starbursts; they correspond to the very “blue” galaxies observed in the UV by FOCA2000 and provide an explanation for the high local SFR determined by Treyer et al. (1998). They also observed in the deeper Cowie et al. (1999) samples and explain the shallower slope found by the authors.

ii) Surprisingly, the SFR of the intermediate-type class increases by a factor six between \( z = 0 \) and 1, not far from the results of most bright surveys (CFRS, H\( \alpha \), FOCA2000, ISO/Deep survey). These results explain why the redshift distribution of the CFRS is well reproduced by our models (Figure 2, top) and could be due to the fact that the observed nearby selected samples (CFRS, H\( \alpha \) and ISO) are biased towards bright spirals.

iii) The SFR of ellipticals and lenticulars evolves rapidly at \( z > 1 \) or 2, which is consistent with the blue population of spheroidals discovered in the Hubble Deep Field.

By comparison with previous determinations of the global SFH, our analysis avoid two problems which could explain the strong difference between Lilly et al., 1996’s and Cowie et al., 1999’s results. First, the conversion factors used to convert the observational tracers to star formation rates (I\( AB \) to 2800\( \AA \), H\( \alpha \) emission lines, far-IR) are very uncertain, mainly because of the extinction correction. Second, every sample suffers from detection limits. Magnitude-limited samples miss nearby faint galaxies while surface brightness-limited samples do not detect high-redshift galaxies because of the \((1 + z)^4\)-fading. This argument, already mentioned by Cowie et al., 1999, is partly avoided when models are fitted on the deepest surveys.

Another interesting point concerns predictions for spirals at \( 1 \leq z \leq 4 \). The SFR vs. \( z \) curve is flat, in agreement with ISOCAM and ISOPHOT results (Aussel et al., 1999; Lagache et al., this conference) after correction of dust effects.

To summarize, the results on a shallow slope of SFH for \( z \leq 1 \) are robust. At higher redshifts, a strong increase of star formation rate is predicted if evolution scenarios of elliptical galaxies are monolithic. However more uncertainties on cosmological parameters or high-z star formation processes as merging, require deeper observations and more detailed analyses at high redshift galaxies, depending on metal, dust and other parameters. Implications on the ionisation at high redshifts, the population of primeval galaxies, all observational programs of the future NGST are strong.
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