

# Significant evolution of the stellar mass-metallicity relation since $z \sim 0.65$

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## ABSTRACT

We present the stellar mass-metallicity relation for 34  $0.4 < z < 1$  galaxies selected from CFRS and Marano fields, and compare it to those derived from three local samples of galaxies (NFGS, KISS and SDSS). Our metal abundance estimates account for extinction effects, as estimated from IR/optical ratios and Balmer line ratios. All three comparisons show that the intermediate mass galaxies at  $z \sim 0.65$  are more metal-deficient by 0.3 dex at a given  $M_K$  or stellar mass relative to  $z = 0$ . We find no evidence that this discrepancy could be related to different methods used to derive mass and metallicity. Assuming a closed box model predicts a gas fraction converted into stars of 20–25% since  $z \sim 0.65$ , if the gas fraction is 10–20% in present-day galaxies with intermediate masses. This result is in excellent agreement with previous findings that most of the decline of the cosmic star formation density is related to the population of intermediate mass galaxies, which is composed of 75% spirals today. We find no evidence for a change of the slope of the  $M_{\text{star}}-Z$  relation from  $z \sim 0.65$  to  $z = 0$  within the intermediate mass range ( $10.5 < \log(M_{\star}) < 11.5$ ).

**Key words.** galaxies: abundances – galaxies: evolution – galaxies: ISM – galaxies: spiral – galaxies: starburst – galaxies: stellar content

## 1. Introduction

The origin of the decline of star formation density over the last 8 Gyr is still a matter of debate. Studies based on spectral energy distributions (SEDs) of galaxies predict that 30% to 50% of the mass locked in stars in present day galaxies condensed into stars at  $z < 1$  (Dickinson et al. 2003; Pozzetti et al. 2003; Drory et al. 2004; Bell 2004). This result is supported by the integrations of the star formation density, especially when it accounts for infrared light (Flores et al. 1999). Indeed, the rapid density evolution of luminous infrared galaxies (LIRGs) suffices in itself to account for the formation of ~40% of the total stellar mass found in intermediate massive galaxies (from  $2 \times 10^{10}$  to  $2 \times 10^{11} M_{\odot}$ , Hammer et al. 1996). As opposed to the idea of galaxy “downsizing” (Cowie et al. 1996) – strong evolution only in the faint blue dwarf population – there is a growing consensus that most of the decline of the star formation density is indeed related to intermediate-mass galaxies (Hammer et al. 2005; Bell et al. 2005). Recall that those account for most of the total stellar mass today, and are crowding the deep redshift surveys at intermediate redshifts. Today, intermediate mass galaxies are mainly spirals, which has led Hammer et al. (2005) to claim that most of the recent mass evolution has occurred in progenitors of spirals.

An important test to confirm this simple scenario for the decline of star formation in the universe is to study the relation

between metal abundances and stellar masses. This can probe either the galaxy “downsizing” scenario (in which case no evolution is expected at intermediate masses) or the findings of Hammer et al. (2005). Previous studies of gas metal content in distant galaxies have related oxygen abundances to absolute  $B$  band luminosities (Kobulnicky & Zaritsky 1999; Kobulnicky et al. 2003; Kobulnicky & Kewley 2004; Liang et al. 2004; Maier et al. 2004, 2005; Lilly et al. 2003; Hammer et al. 2005, etc.). Most of these studies led to the conclusion for evolution of the  $M_B-(O/H)$  relation, although there are some differences in the magnitude of the evolution. The oxygen abundances are derived from  $R_{23} = [O II]\lambda 3727/H\beta + [O III]\lambda 4959,5007/H\beta$ , it is vital to properly estimate the  $[O II]\lambda 3727/H\beta$  ratio, which thus imply to derive as accurate as possible the extinction correction factor. Liang et al. (2004) and Hammer et al. (2005) used very deep spectroscopy of distant galaxies at VLT to derive extinction corrected  $R_{23}$  values, on the basis of a check of the extinction correction, using both Balmer line ratio (after a proper correction for the underlying absorption) and the IR/visible light ratio. They claimed an evolution of the  $M_B-(O/H)$  relation by ~0.3 dex at  $z = 0.7$ , if this evolution is associated with a dimming of the metal abundance at high redshift. However, because blue light is easily affected by star formation events, it is possible that a significant part of the evolution is caused by a brightening (of 2.5 mag) in the blue band.

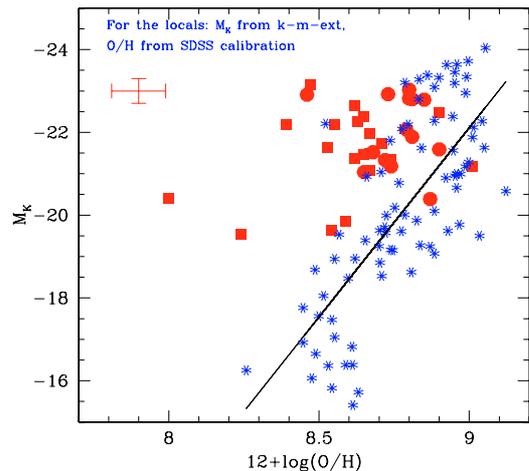
The near-IR  $K$ -band luminosity is less affected by star formation and by dust than the  $B$ -band luminosity, and is more directly related to the stellar mass (Charlot 1998; Bell & de Jong 2000). Therefore, in this study, we have derived the mass (or  $M_K$ )-metallicity relations for a sample of intermediate- $z$  galaxies, and compared them with those for local galaxies. The paper is organized as follows: Sect. 2 describes the observational data; Sect. 3 describes the methodology adopted to ensure a fair comparison with local galaxies; results and analyses are given in Sect. 4; and Sect. 5 gives the conclusion. Throughout this paper, a cosmological model with  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.3$  and  $\Omega_\Lambda = 0.7$  has been adopted. The AB magnitude system was used.

## 2. Observational data

The VLT/FORS observations of our intermediate- $z$  galaxies have been described in Hammer et al. (2005) and Liang et al. (2004). In addition, we have measured stellar masses for seven additional objects which possess estimated metal abundances. In total (see Table 1), 34 star-forming galaxies (non-AGNs from the diagnostic diagram) with  $z > 0.4$  are selected from the Canada-France-Redshift Survey (CFRS) and Marano fields (the Ultra Deep Fields) with both of their oxygen abundances and  $K$ -band absolute magnitudes available, including luminous IR galaxies (LIRGs), and starbursts.

The metallicities of the sample galaxies were estimated from the extinction-corrected  $R_{23}$  parameters to be converted to oxygen abundances by using the calibration derived from SDSS data by Tremonti et al. (2004). We must keep in mind that the only way to derive O/H metal abundances of galaxies with sufficient accuracy is by deriving the extinction and the underlying Balmer absorption properly, on the basis of good-S/N spectra of moderate resolution. The high quality VLT/FORS spectroscopic data help us to obtain reliable oxygen abundances of the sample galaxies. As discussed in Liang et al. (2004), the corresponding error budget of emission line flux is deduced by a quadratic addition of three independent errors: the use of stellar templates to fit stellar absorption lines and continuum; the differences among independent measurements performed by Y. C. Liang, H. Flores and F. Hammer; and the Poisson noises from both sky and object spectra. Therefore, most of the uncertainties of  $12 + \log(\text{O}/\text{H})$  range from 0.03 to 0.30 dex with the average value of 0.10 dex and the typical value of 0.09 dex (omitting one object with big error bar which was not used in the actual statistics, see Table 1).

The stellar masses of these galaxies were estimated from  $K$ -band magnitudes. We have chosen a conservative approach, which assumes that  $M/L_K$  depends on the rest-frame  $B - V$  color following the relation derived by Bell et al. (2003) (see Hammer et al. 2005, for more details). Sources of error include uncertainties from magnitude errors, systematic uncertainties in stellar  $M/L$  ratio from dust and bursts of Star Formation (SF), and Poisson errors. The typical uncertainty of the estimated  $M_K$  is about  $\pm 0.3$  dex. The typical error bars of the estimates of the sample galaxies have been plotted on the left-top in Fig. 1.



**Fig. 1.**  $M_K$ -metallicity relation for the intermediate- $z$  galaxies (red symbols) and local spirals (blue stars) from the NFGS. The red filled circles refer to distant LIRGs ( $\text{SFR} > 20 M_\odot/\text{yr}$ ) and the red filled squares refer to distant starburst galaxies ( $\text{SFR} < 20 M_\odot/\text{yr}$ ). Abundances have been generated following the Tremonti et al. (2004) calibration for all galaxies with typical uncertainty of 0.09 dex, which has been plotted on the left-top on the figure, together with the typical uncertainty of  $M_K \sim 0.3$  mag. Straight line is the best fit for the NFGS galaxies ( $y = -9.15x + 60.23$ ). Because the intermediate- $z$  galaxies sample a much shallower range in  $M_K$ , we won't fit them. Recall that these galaxies have been selected in  $I$ -band (or  $B$  or  $V$  at rest), which leads us to suspect that some galaxies might have been missed at  $M_K > -21$ .

## 3. Comparison to three samples of local galaxies: NFGS, KISS and SDSS data

We have considered three local samples for comparison with our intermediate- $z$  galaxies. They are the Nearby Field Galaxy Survey (NFGS, Jansen et al. 2000a,b), which is a sample of local spirals, the KPNO International Spectroscopic Survey (KISS, Salzer et al. 2005), which is a sample of local starburst galaxies selected by their  $H\alpha$  emission line, and the Sloan Digital Sky Survey (SDSS, Tremonti et al. 2004). Because most local galaxies with emission lines are spirals, it is expected that the NFGS and SDSS should provide essentially a similar luminosity vs. metal relation. In the following we describe in detail how we have carried out the local data to ensure that the estimates of both O/H and  $M_K$  (or stellar masses) have been done in a similar manner for local and for distant samples. A brief description of the comparison is presented in Figs. 1–3.

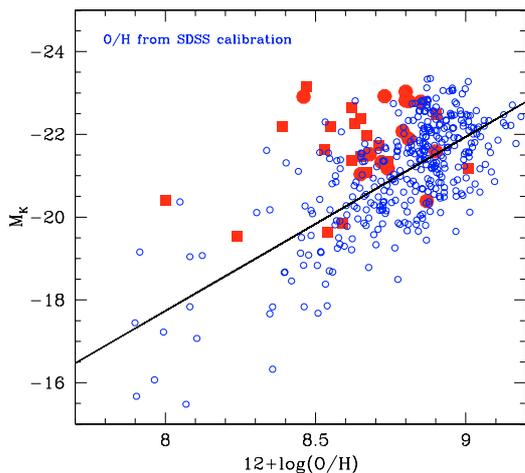
### 3.1. Comparison to local spirals from the NFGS

Jansen et al. (2000a,b) have published the emission line fluxes for their 198 nearby field galaxies, including  $[\text{O II}]$ ,  $[\text{O III}]$ ,  $H\beta$ ,  $H\alpha$  etc. This makes it possible for us to directly estimate the dust extinction of the galaxies by assuming the same extinction law as we used in Liang et al. (2004), and then to derive their oxygen abundances. We use the SDSS calibration from Tremonti et al. (2004) to convert  $R_{23}$  in oxygen abundances for all sources.

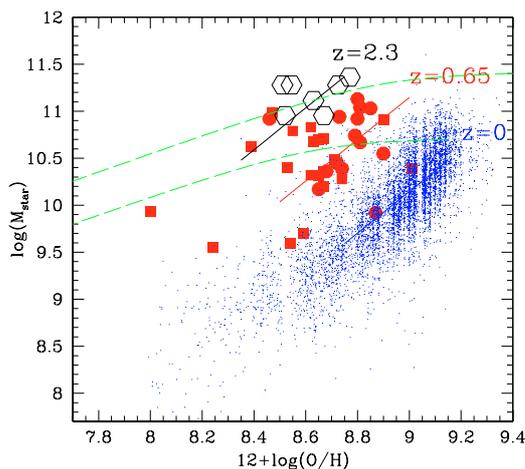
**Table 1.** The basic parameters of the sample of distant galaxies for stellar mass-metallicity relation: only the galaxies with  $\log(M/M_\odot) > 9.5$ . “997” means the line is blended with sky; “998” means no corresponding line detected at the line position; “999” means the line is shifted outside the rest-frame wavelength range. The last column gives more notes for several objects, “LINER” means the Low Ionization Nuclear Emission line Region classified by following the  $[\text{OII}]/\text{H}\beta$  vs.  $[\text{OIII}]/\text{H}\beta$  relation.

CFRS	$z$	$M_K$	$\log(M/M_\odot)$	$12 + \log(\text{O}/\text{H})$	$R_{23}$	[OII]	[OIII]	H $\beta$	Note
00.0137	0.9512	-23.15	10.98	$8.47 \pm 0.13$	Yes				
00.0141	0.4401	-21.49	10.36	$8.67 \pm 0.10$	No	999			
00.0564	0.6105	-21.61	10.44	–	No	999	998		
00.1721	0.5581	-21.09	10.20	$8.67 \pm 0.05$	Yes				
03.0006	0.8836	-19.59	9.58	–	No		999	999	
03.0035	0.8804	-23.11	11.07	–	No		999	999	
03.0062	0.8252	-22.68	10.87	–	No		999	999	
03.0085	0.6100	-20.80	10.10	–	No			997	
03.0174	0.5250	-20.87	10.16	–	Yes				LINER
03.0186	0.5220	-21.95	10.61	–	Yes				LINER
03.0422	0.7150	-22.47	10.76	–	No		999		
03.0442	0.4781	-20.40	9.93	$8.05 \pm 0.30$	Yes				
03.0445	0.5300	-22.07	10.74	$8.79 \pm 0.07$	Yes				
03.0507	0.4660	-21.04	10.17	$8.65 \pm 0.05$	Yes				
03.0523	0.6508	-21.52	10.36	$8.68 \pm 0.09$	Yes				
03.0533	0.8290	-22.41	10.73	–	No		999	999	
03.0570	0.6480	-20.39	9.92	$8.87 \pm 0.27$	Yes				
03.0589	0.7160	-21.08	10.21	–	No		999	997	
03.0595	0.6044	-21.44	10.35	–	No				no A <sub>V</sub>
03.0645	0.5275	-21.34	10.28	$8.74 \pm 0.09$	Yes				
03.0776	0.8830	-20.65	10.02	–	Yes				LINER
03.0932	0.6478	-22.82	10.92	$8.80 \pm 0.19$	Yes				
03.1309	0.6170	-22.91	10.92	$8.46 \pm 0.11$	Yes				
03.1349	0.6155	-22.92	10.94	$8.73 \pm 0.06$	Yes				
03.1531	0.7148	-22.28	10.72	–	No		998	997	
03.1540	0.6898	-22.31	10.70	–	No	997			
03.1541	0.6895	-21.18	10.39	$8.74 \pm 0.09$	Yes				
22.0242	0.8638	-22.27	10.68	$8.63 \pm 0.26$	Yes				
22.0344	0.5168	-19.84	9.70	$8.59 \pm 0.06$	Yes				
22.0429	0.6243	-21.72	10.48	$8.71 \pm 0.15$	Yes				
22.0576	0.8905	-21.46	10.32	$8.65 \pm 0.14$	Yes				
22.0599	0.8854	-22.19	10.62	$8.39 \pm 0.06$	Yes				
22.0626	0.5150	-19.64	9.59	$8.54 \pm 0.09$	No	999			
22.0637	0.5419	-21.37	10.32	$8.62 \pm 0.08$	Yes				
22.0721	0.4070	-20.46	9.99	–	No	999			
22.0779	0.9252	-22.37	10.70	$8.65 \pm 0.12$	Yes				
22.0828	0.4070	-20.53	10.01	–	No	999			
22.0919	0.4714	-19.55	9.55	$8.24 \pm 0.03$	Yes				
22.1064	0.5369	-21.64	10.40	$8.53 \pm 0.07$	Yes				
22.1070	0.8796	-22.65	10.83	$8.62 \pm 0.27$	Yes				
UDSR									
08	0.7291	-21.33	10.45	$8.72 \pm 0.04$	Yes				
10	0.6798	-23.03	11.13	$8.80 \pm 0.07$	Yes				
14	0.8150	-22.79	11.03	$8.85 \pm 0.26$	Yes				
15	0.4949	-21.89	10.67	$8.81 \pm 0.05$	No	999			
23	0.7094	-22.80	11.04	$8.81 \pm 0.05$	Yes				
26	0.3841	-22.19	10.79	$8.55 \pm 0.24$	Yes				
UDSF									
02	0.7781	-21.97	10.71	$8.67 \pm 0.49$	Yes				
03	0.5532	-21.59	10.55	$8.90 \pm 0.07$	Yes				
07	0.7014	-22.48	10.91	$8.90 \pm 0.10$	Yes				
16	0.4548	-21.19	10.39	$9.01 \pm 0.04$	Yes				

The  $K$ -band magnitudes of the NFGS sample were derived from 2MASS (Extended Source Catalog, see <http://irsa.ipac.caltech.edu/applications/Gator/>). Four magnitudes were obtained: k-m-k20fe ( $K$  20 mag/sq.),



**Fig. 2.**  $M_K$ -metallicity relation for the intermediate- $z$  galaxies and for the local KISS starbursts. Same symbols as in Fig. 1 are used for distant galaxies, and the local starbursts are represented by blue open circles. Abundances have been generated following the Tremonti et al. (2004) calibration for all galaxies. The straight line is the best fit for the KISS galaxies ( $y = -4.21x + 15.93$ ).



**Fig. 3.** Stellar mass-metallicity relation for the SDSS galaxies ( $z = 0$ , Tremonti et al. 2004; Bell et al. 2003, see text), the intermediate- $z$  galaxies ( $z \sim 0.65$ , same symbols as in Fig. 1) and the 7 galaxies (black open hexagon) at  $z = 2.3$  described by Shapley et al. (2004). Abundances have been generated following the Tremonti et al. (2004) calibration for all galaxies. Here we consider SDSS galaxies with  $\log(M_{\text{star}}) > 9.5$  which are fitted by a straight line with  $y = 2.22x - 9.83$ . This choice has been motivated by the fact that all intermediate- $z$  galaxies have a stellar mass above this cut-off. By forcing the lines to fit the median of intermediate distant galaxies and of  $z = 2.3$  galaxies, we find an evolution of  $-0.4$  dex and  $-0.7$  dex in metal abundances, respectively. The green long-dashed lines show the result of a closed box model and indicating the general evolutionary trend from  $z = 2.3$  and  $z = 0.65$  to  $z = 0$ , respectively (see text).

the isophotal fiducial ell. ap. magnitude; k-m-fe, the  $K$  fiducial Kron ell. mag aperture magnitude; k-m-ext, the  $K$  mag from fit extrapolation; and k-m-e, the  $K$  Kron elliptical aperture magnitude. Here we just consider the k-m-ext mag (the  $K$  mag from fit extrapolation), which was assumed to better trace the galactic luminosity.

Figure 1 plots the  $M_K$ -metallicity relations for our sample galaxies, compared with the local sample from NFGS (E and S0 galaxies have been removed here). For distant galaxies, the median oxygen abundance is  $12 + \log(\text{O}/\text{H}) = 8.67$  at the median  $M_K = -21.74$ , which is  $\sim 0.3$  dex lower (i.e.  $\sim 50\%$  more metal deficient) than the local ones. Recall that the discrepancy is significantly larger than typical uncertainties.

### 3.2. Comparison to local starbursts from the KISS

Salzer et al. (2005) derived the luminosity-metallicity relation in both optical and the near IR ( $J$ ,  $H$ ,  $K$  bands from 2MASS) for the KISS data. Oxygen abundances based on the SDSS calibration were used here.

Figure 2 reveals a similar discrepancy as seen in Fig. 1 when comparing the distant to the nearby galaxies. However, we notice that the local starbursts show a wide dispersion around the linear least-square fit (also see Salzer et al. 2005) and hence that there is a significant overlap between the local and distant starbursts.

### 3.3. Comparison to SDSS galaxies

SDSS provides a powerful database to study the formation and evolution of galaxies. Tremonti et al. (2004) have published the metallicities and stellar masses for  $\sim 53\,400$  galaxies. Bell et al. (2003) re-derived the stellar masses of a sub-sample of the SDSS galaxies using  $K$  band data from 2MASS, and we choose to use them to be consistent with our derived stellar masses. Notice that the estimates obtained by Bell et al. provides stellar masses slightly smaller than Tremonti et al.'s estimates with the discrepancy increasing at the high mass end (it is  $\sim 0.17$  dex at  $\log(M_{\star}) = 10.5$ ). Recall that a Kroupa (2001) IMF was used in Tremonti et al. (2004), whereas Bell et al. (2003) adopted the Salpeter IMF. Figure 3 is confirming the results from Figs. 1 and 2, and at the median stellar mass of the distant galaxies ( $\log(M_{\star}) = 10.55$ ), their median abundance is 0.4 dex lower than the local SDSS galaxies. One can rule out that this effect can be related to differences in the estimation of the stellar masses, as it remains when considering absolute  $K$  band luminosities.

## 4. Strong evolution of the stellar mass ( $M_K$ )-metallicity relation

We have compared the metal abundance properties of a sample of 34 galaxies from  $z = 0.4$  to  $z = 1$  (median redshift  $z = 0.65$ ) to those of nearby galaxies. We carefully estimate oxygen abundances and stellar masses in a similar way for both distant and nearby galaxies. It shows that the 34 distant galaxies show a distribution that is systematically shifted towards lower abundances when compared to local galaxies. Because the amplitude of the effect is much larger than the error budget, it is tempting to claim that the stellar mass-metallicity relation has strongly evolved since  $z \sim 0.65$ , or in other words, that intermediate mass galaxies at  $z \sim 0.65$  have on average half of the metal content of local counterparts in their gaseous phase.

Before trying to derive firm conclusions from this result, let us investigate if some systematics are involved.

First, the emission line regions sampled by the slit (or fiber for the SDSS) for local galaxies do not account for all the galaxy, unlike the case for small and faint distant galaxies. However, the effect should be modest here. The emission line fluxes quoted by Jansen et al. (2000a,b) have been obtained after scanning of the overall galaxies in the NFGS (the integrated ones). Tremonti et al. (2004) obtained the Bayesian metallicity estimates by using the approach outlined by Charlot et al. (2005), based on simultaneous fits of all the most prominent emission lines, with a model designed for the interpretation of integrated galaxy spectra (Charlot & Longhetti 2001). They have checked the relations between their Bayesian metallicity estimates and the  $R_{23}$  values, which are consistent with the relations from literature, including McGaugh (1991) and Zaritsky et al. (1994). One may worry about the  $3''$  fiber diameter of SDSS will focus more on the nuclear part of the spectra of the galaxies, and cause slightly higher metallicity estimates than the global ones. Indeed, Kewley et al. (2005) has discussed this aperture effect on the basis of the NFGS spectra. They concluded that, since the sample galaxies studied by Tremonti et al. (2004) range in redshift between  $0.03 < z < 0.25$ , the aperture effects are not significant in the metallicity estimates and the  $L-Z$  relations. Salzer et al. (2005) have argued that their metallicity estimates may be slightly higher than the integrated values for the extended spirals due to the abundance gradients. The reported evolution of the stellar mass-metallicity at  $z \sim 0.65$  is observed after comparing to either NFGS, KISS or SDSS, so we believe that aperture effects are likely modest.

Second, to what extent is our sample representative of the distant galaxy population, and could selection effects partly or fully explain our result? Most of the galaxies have been selected from the CFRS and from the Ultra Deep Fields (see Liang et al. 2004). Originally, this sample of  $M_B < -20$  galaxies was defined to include a significant fraction of LIRGs. Indeed those constitute 38% of the sample, while Hammer et al. (2005) estimated the fraction of LIRGs to be 15% in a sample of distant and intermediate mass galaxies. We compared (see Figs. 1 to 3) the populations of LIRGs and starbursts in our sample. Applying a Kolmogorov-Smirnov test provides that their distributions in  $M_K$  are similar, with a Student's parameter  $t = 1.1$  (the probability for the two sub-samples drawn from a different population is 30%). Moreover, LIRGs show on average a higher O/H ratio than starbursts at a marginal level, with a Student's parameter  $t = 2.2$  (the probability for the two sub-samples drawn from a different population is 97%). This marginal effect is expected because LIRGs are producing metals and stars at a very efficient rate. So, introducing an excessive number of LIRGs in our sample could only minimize the discrepancy that we find with local samples.

Third, we have to investigate if the effect is actually due to a deficiency of metals at a given stellar mass (or  $M_K$  magnitude) or if it could be related to a brightening of the distant galaxies. At the median oxygen abundance ( $12 + \log(\text{O}/\text{H}) = 8.67$ ) the brightening in  $K$  band magnitude would be  $\Delta M_K = 2.7$  mag (see Fig. 1), which should be compared to  $\Delta M_B = 3.1$  for the same sample (see Fig. 4 of Hammer et al. 2005). Such a

huge brightening at all wavelengths is simply not plausible: it could occur only if almost all the light in all distant emission line galaxies would be associated with very young stars and strong dust. One has to remind that the spectra of all intermediate mass galaxies show a mixture of young, intermediate age and old stars, as evidenced by Balmer and metal (CaII HK, CaI,  $G$ -band, MgI) absorption lines (see Hammer et al. 2005). We believe it is more natural that the important population of distant emission line galaxies (at  $z = 0.65$ , 65% of  $M_B < -20$  galaxies have  $W_0(\text{OII}) > 15 \text{ \AA}$ , see Hammer et al. 1997) evolve at almost a constant luminosity into comparatively metal-rich disk galaxies in the local universe, rather than to fade into dwarf galaxies.

The closed box model for the evolution of galaxies (without gas inflow or outflow) allows us the possibility to crudely estimate the evolution of the gaseous content. Following Kobulnicky & Kewley (2004; see the original version in Searle & Sargent 1972; and Tinsley 1980), the metallicity  $Z$  is related to the gas mass fraction  $\mu = M_{\text{gas}}/(M_{\text{gas}} + M_{\text{star}})$ , by:

$$Z = Y \ln(1/\mu),$$

where  $Y$  is the yield. By differentiating this relation, we note that a change in metallicity with gas mass fraction is independent of the yield and is given by (see Kobulnicky & Kewley 2004):

$$d(\log Z)/d\mu = 0.434/(\mu \ln(\mu)).$$

In Fig. 3, we have plotted the closed box model evolution assuming the median point of our sample ( $12 + \log(\text{O}/\text{H}) = 8.67$  and  $\log(M_\star) = 10.55$  at a median redshift of 0.65), which links it to a local galaxy in the Tremonti et al. (2004) sample with  $12 + \log(\text{O}/\text{H}) = 9.15$  and  $\log(M_\star) = 10.7$ . For the local galaxy we assume a gas fraction  $\mu = 10\%$ , which implies a median gas fraction at  $z = 0.65$  of 30%. In other words, in a closed box model, a present-day spiral would have converted 20% of its total mass from gas to stars during that redshift interval. Assuming a higher gas mass fraction today ( $\mu = 20\%$ ), it would increase the gas-to-star converted mass fraction to 25% since  $z = 0.65$ . These values are significantly higher than those found by Kobulnicky & Kewley (2004), and such a discrepancy is explained in the section below.

#### 4.1. Comparison with other studies of intermediate- $z$ galaxies

There is only one study that can be directly compared to our result, namely, the paper presented by Savaglio et al. (2005), in the frame of the Gemini Deep Deep Survey (GDDS). Their method (flux calibration, removing of underlying absorption etc.) is essentially similar to ours. Their sample consists of 27  $0.4 < z < 1$  galaxies with only 4 of them having  $\log(M_{\text{star}}) > 10$ , i.e. GDDS galaxies are far less massive than those presented here. They found an average extinction of  $A_V = 2.2$  for their sample, a value similar to that found by Liang et al. (2004) but significantly higher than  $A_V = 1$ , a value assumed by Lilly et al. (2003). Notice that one third of the Lilly et al. (2003) sample is made of LIRGs and that the

inferred metallicity assuming  $A_V = 1$  leads to values  $\sim 0.3$  dex larger than our estimates based on a proper correction of the  $[\text{O II}]\lambda 3727/\text{H}\beta$  ratio. Indeed Savaglio et al. (2005) also find a significant evolution of the mass-metallicity relation. However, comparison to their results is complicated by the fact that they have merged their sample (low masses, on which they assumed  $A_V = 2.2$ ) to that of Lilly et al. (high masses, on which they assumed  $A_V = 1$ ). Recall that for starbursts, a general correlation is expected between mass, metallicity, dust and then extinction which contradicts the Savaglio et al. (2005) assumption. This is particularly true at intermediate redshift and the emergence of relatively massive LIRGs at  $z > 0.4$  (Hammer et al. 2005) is evidence of the serious impact of extinction effects in estimating the evolution of the stellar mass-metallicity relationship.

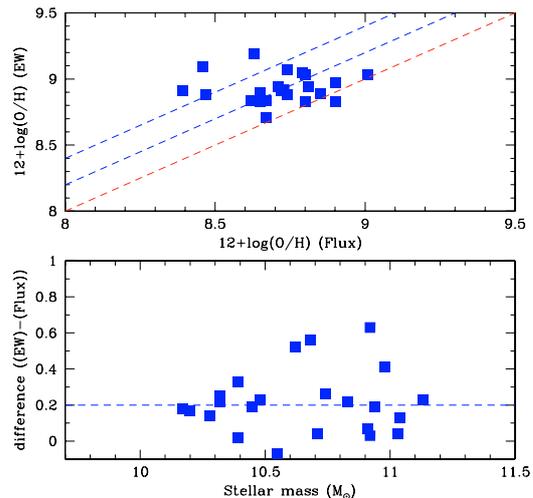
Kobulnicky & Kewley (2004) have described the metal- $M_B$  relation of 204 galaxies in the GOODS-North field, and found a much more moderate evolution than us. By comparing their result to that of Liang et al. (2004) or Hammer et al. (2005), they found at a constant  $M_B$  a decrease in metal abundance of 0.14 dex from  $z = 0$  to 1, which compares to 0.3 dex from  $z = 0$  to  $z = 0.7$  in Hammer et al. (2005). Because there are no evidence indicating any serious difference in the selection of galaxies between the various studies, we investigate if this could be due to the different methodologies adopted here and there. Recall that Kobulnicky & Kewley (2004) have to derive  $R_{23}$  parameters from equivalent width ratios, because they are using non flux calibrated spectra. Their method has been calibrated from systematic comparison to the KISS and NFGS samples (see Kobulnicky & Phillips 2003).

To do so, we have applied for our sample the equivalent width methodology, and Fig. 4 compares the values derived by both methods. Notice that the equivalent width method producing systematically higher metal abundance by  $\sim 0.2$  dex, which is likely to be the origin of the discrepancy. Indeed the discrepancy is even higher for large masses and large extinction coefficients: Kobulnicky & Kewley (2004) were finding an absence of evolution at the high mass end, which is not confirmed by our study. We suspect that the Kobulnicky and Phillips calibration might not apply to distant starbursts because those show on average, larger extinction coefficient than local galaxies.

#### 4.2. Comparison to higher redshift galaxies

Shapley et al. (2004) presented the near IR spectroscopic measurements for seven star-forming galaxies at  $2.1 < z < 2.5$ . The oxygen abundances of these galaxies were estimated by using  $[\text{N II}]/\text{H}\alpha$  ratio following calibrations from Pettini & Pagel (2004) and Denicolo et al. (2002), and show  $12 + \log(\text{O}/\text{H}) = 8.47\text{--}8.69$  and  $8.56\text{--}8.80$ , respectively, which are  $\sim 0.3\text{--}0.4$  dex lower than solar values. Shapley et al. (2004) found that these galaxies already possess stellar masses in excess of  $10^{11} M_\odot$ .

Figure 3 presents the variance of the stellar mass – metallicity relation at  $z = 0, 0.65$  and  $2.3$ . At  $z = 0.65$ , galaxies with  $\log(M_{\text{star}}) > 10.5$  or with  $10 < \log(M_{\text{star}}) < 10.5$  are metal deficient when compared to SDSS galaxies: from the small data set presented here, there is no evidence for an



**Fig. 4.** *Top:* comparison of metal abundances derived from extinction corrected flux ratio and those derived following the equivalent width method as it is described in Kobulnicky & Kewley (2004); *bottom:* shows the difference of oxygen abundances from the two methods against the stellar masses.

evolution of the slope of the stellar mass-metallicity relationship. Because at  $z = 0.65$  (and more obviously at  $z = 2.3$ ) only high stellar masses are included, we therefore consider in the following an absence of slope evolution. To fit  $z = 0.65$  and  $z = 2.3$  galaxies, it is required to shift the local relation by  $-0.4$  and  $-0.7$  dex in metal abundance, respectively. Assuming a closed box model, would lead to median gas fractions of 30% and 45% at  $z = 0.65$  and  $z = 2.3$ , respectively. In the absence of knowledge of the evolution of metal abundance for  $z = 2.3$  intermediate mass galaxies, it is difficult to translate these values directly to average mass formation within the  $z = 0.65\text{--}2.3$  interval. Nevertheless, combining of our result with that of Savaglio et al. (2005) suggests a formation of 1/5 to 1/4 of the stellar mass in most present day spirals since  $z = 0.65$ , which agrees rather well with expectations from stellar mass density studies (see Drory et al. 2004). Recall that it matches well with the 40% of stellar mass formed since the last 8 Gyr claimed by Hammer et al. (2005) from integrations of the IR star formation rate density.

#### 5. Conclusion: gas converted to stars since the last 8 Gyr

There is a growing consensus that a significant part of the masses of the present-day spirals were formed since  $z = 1$  (Hammer et al. 2005; Bell et al. 2005). According to Drory et al. (2004, see their Fig. 7), the stellar mass density at  $z \sim 0.65$  is roughly 75% that at  $z = 0$ . This result matches well with the integrated star formation density, if IR light is taken into account. Here we have shown that it also matches with the evolution of the gaseous fraction in galaxies, which leads, under our assumption of a closed box model, to 20–25% of the gas which has been transformed into stars since  $z = 0.65$ . Of course, a closed box model is a very crude approximation of the evolution of intermediate mass galaxies, which can be affected by gas outflow, inflow and minor or major mergers. However,

as a whole, the intermediate mass galaxy population can be assumed to characterize most of the gas to mass ratio of the universe, and applying a closed box model to this population allows comparison to other integrated quantities such as stellar mass or star formation densities.

We find no evidence for a change in the slope of the  $M_{\text{star}}-Z$  relation. Notice that many studies (Lilly et al. 2003; Kobulnicky & Kewley 2004) found no evolution for the higher mass range of their sample, which has been interpreted as evidence for the “downsizing” scenario. While our data are not that different from those of the above studies, we do find evidence that intermediate mass galaxies show under-abundances when compared to local galaxies. Our method accounts for a proper correction for extinction, that being derived from both the IR/optical ratio and Balmer line ratio. Recall that extinction potentially affects more noticeable the metal abundance estimates of massive starbursts, and that it may lead to erroneous conclusions when its effect is neglected. In a forthcoming paper (Flores et al., in preparation), we will compare our oxygen abundances to those from the  $[\text{N II}]/\text{H}\alpha$  ratio which is essentially independent of extinction.

There are also many recent publications that discuss the assembly history of galaxies. It has been shown that the specific star formation rate ( $\text{SFR}/M_{\text{star}}$ ) is anti-correlated with the stellar mass in the local Universe (see Brinchmann et al. 2004), and the  $b$ -parameter ( $\text{SFR}/\langle\text{SFR}\rangle$ ) on average decreases with mass for the late-type galaxies (Salim et al. 2005). At higher redshift, a similar trend was found in several studies using various SFR tracers from UV to mid-IR (Bauer et al. 2005; Feulner et al. 2005a,b; Perez-Gonzalez et al. 2005). All these studies suggest a “downsizing”, in the way that, on average, massive galaxies have lower specific star formation rates than those with lower mass. Papovich et al. (2004) and Bundy et al. (2005) obtained similar results. Indeed, the metallicities of galaxies must be an excellent indicator to explore this issue, because it links two independent quantities ( $M_{\text{star}}-\text{O}/\text{H}$ ). We notice however that this study cannot be conclusive for or against the “downsizing”, because the present sample includes too few objects in a too restricted mass range. In the near future we will be able to better test this by including a much larger set of measurements ( $\sim 200$  intermediate redshift galaxies), in the frame work of a large program at VLT.

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## References

- Bauer, A. E., Drory, N., Hill, G. J., & Feulner, G. 2005, *ApJ*, 621, L89
- Bell, E. F. 2004, invited review in *Planets to Cosmology: Essential Science in Hubble’s Final Years*, ed. M. Livio (Cambridge: CUP), [arXiv:astro-ph/0408023]
- Bell, E. F., & de Jong, R. S. 2000, *MNRAS*, 312, 497
- Bell, E. F., McIntosh, D. H., Katz, N., et al. 2003, *ApJS*, 149, 289
- Bell, E. F., Papovich, C., Wolf, C., et al. 2005, *ApJ*, 625, 63
- Brinchmann, J., Charlot, S., White, S. D. M., et al. 2004, *MNRAS*, 351, 1151
- Bundy, K., Ellis, R. S., & Conselice, C. J. 2005, *ApJ*, 625, 621
- Charlot, S. 1998, in *The next generation space telescope: science drivers and technological challenges*, 34th Liège Astrophysical Coll., 135
- Charlot, S., et al. 2005, in preparation
- Charlot, S., & Longhetti, M. 2001, *MNRAS*, 323, 887
- Cowie, L. L., Songaila, A., Hu, E. M., & Cohen, J. G. 1996, *AJ*, 112, 839
- Dickinson, M., Papovich, C., Ferguson, H. C., et al. 2003, *ApJ*, 587, 25
- Denicolo, G., Terlevich, R., & Terlevich, E. 2002, *MNRAS*, 330, 69
- Drory, N., Bender, R., Feulner, G., et al. 2004, *ApJ*, 608, 742
- Feulner, G., Goranova, Y., Drory, N., et al. 2005a, *MNRAS*, 358, L1
- Feulner, G., Gabasch, A., Salvato, M., et al. 2005b, *ApJ*, 633, L9
- Flores, H., Hammer, F., Thuan, T. X., et al. 1999, *ApJ*, 517, 148
- Flores, H., Proust, D., & Hammer, F. 2005, in preparation
- Hammer, F., Le Fèvre, O., Lilly, S. J., et al. 1997, *ApJ*, 481, 49
- Hammer, F., Flores, H., Elbaz, D., et al. 2005, *A&A*, 430, 115
- Jansen, R. A., Franx, M., Fabricant, D., & Caldwell, N. 2000a, *ApJS*, 126, 271
- Jansen R. A., Fabricant, D., Franx, M., & Caldwell, N. 2000b, *ApJS*, 126, 331
- Kewley, L. J., Jansen, R. A., & Heller, M. J. 2005, *PASP*, 117, 227
- Kobulnicky, H. A., & Zaritsky, D. 1999, *ApJ*, 511, 118
- Kobulnicky, H. A., & Phillips, A. 2003, *ApJ*, 599, 1031
- Kobulnicky, H. A., & Kewley, L. J. 2004, *ApJ*, 617, 240
- Kobulnicky, H. A., Willmer, C. N. A., Weiner, B. J., et al. 2003, *ApJ*, 599, 1006
- Kroupa, P. 2001, *MNRAS*, 322, 231
- Liang, Y. C., Hammer, F., Flores, H., et al. 2004, *A&A*, 423, 867
- Lilly, S. J., Carollo, C. M., & Stockton, A. N. 2003, *ApJ*, 597, 730
- Maiher, C., Lilly, S. J., Carollo, M., et al. 2005, *ApJ*, 634, 849
- Maiher, C., Meisenheimer, K., & Hippelein, H. 2004, *A&A*, 418, 475
- McGaugh, S. S. 1991, *ApJ*, 380, 140
- Papovich, C., Dickinson, M., Giavalisco, M., et al. 2005, *ApJ*, 631, 101
- Perez-Gonzalez, P. G., Rieke, G. H., Egami, E., et al. 2005, *ApJ*, 630, 82
- Pettini, M., & Pagel, B. E. J. 2004, *MNRAS*, 348, L59
- Pozzetti, L., Cimatti, A., Zamorani, G., et al. 2003, *A&A*, 402, 837
- Salim, S., Charlot, S., Rich, R. M., et al., 2005, *ApJ*, 619, L39
- Salpeter, E. E. 1955, *ApJ*, 121, 161
- Salzer, J. J., Lee, J. C., Melbourne, J., et al. 2005, *ApJ*, 624, 661
- Searle, L., & Sargent, W. L. W. 1972, *ApJ*, 173, 25
- Shapley, A. E., Erb, D. K., Pettini, M., et al. 2004, *ApJ*, 612, 108
- Savaglio, S., Glazebrook, K., Le Borgne, D., et al. 2005, *ApJ*, in press, [arXiv:astro-ph/0508407]
- Tinsley, B. M. 1980, *Fundam. Cosmic Phys.*, 5, 287
- Tremonti, C. A., Heckman, T. M., Kauffmann, G., et al. 2004, *ApJ*, 613, 898
- Zaritsky, D., Kennicutt, R. C., & Huchra, J. P. 1994, *ApJ*, 420, 87