THE DEPENDENCE OF STAR FORMATION ON GALAXY STELLAR MASS
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ABSTRACT
We combine Spitzer 24 μm observations with data from the COMBO-17 survey for ~15,000 0.2 ≤ z ≤ 1 galaxies to determine how the average star formation rates (SFRs) have evolved for galaxy subpopulations of different stellar masses. In the determination of (SFR), we consider both the ultraviolet (UV) and the infrared (IR) luminosities, and account for the contributions of galaxies that are individually undetected at 24 μm through image stacking. For all redshifts, we find that higher mass galaxies have a substantially lower specific SFR, (SFR)/M*, than lower mass ones. However, we find that the striking result that the rate of decline in cosmic SFR with redshift is nearly the same for massive and low mass galaxies, i.e., not a strong function of stellar mass. This analysis confirms one version of what has been referred to as “downsizing,” namely, that the epoch of major mass buildup in massive galaxies is substantially earlier than the epoch of mass buildup in low-mass galaxies. Yet it shows that star formation activity is not becoming increasingly limited to low-mass galaxies toward the present epoch. We argue that this suggests that heating by AGN-powered radio jets is not the dominant mechanism responsible for the decline in cosmic SFR since z ~ 1, which is borne out by comparison with semianalytic models that include this effect.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: general

1. INTRODUCTION

A key observable statistic that describes the evolution of the galaxy population is the average SFR as a function of epoch and of galaxy stellar mass. Over the last decade, much progress has been made toward delineating, and in part understanding, the relationship between star formation history and stellar mass. “Archaeological” studies of present-day galaxies demonstrate a strong correlation between star formation history and present-day stellar mass in the sense that the bulk of stars now in massive galaxies must have formed at earlier epochs than stars now in less massive galaxies (e.g., Kauffmann et al. 2003; Thomas et al. 2005; Gallazzi et al. 2005; Panter et al. 2006). Surveys of cosmologically distant galaxies have revealed a related trend, often referred to as “downsizing” in that context. Downsizing most commonly refers to the observation that intense star formation (M*/SFR ≲ 4M⊙/yr) becomes increasingly limited to systems of lower and lower mass as redshift decreases (Cowie et al. 1996; Chapman et al. 2003; Juneau et al. 2005; Bauer et al. 2005; Feulner et al. 2005; Daddi et al. 2005; Bell et al. 2005; Papovich et al. 2006). Recently, this phenomenon has been recast in more quantitative terms through the study of the specific SFR (SSFR; i.e., SFR per unit stellar mass) as a function of redshift, finding that at z ≲ 1, low-mass galaxies appear to be forming stars at a higher rate per unit mass than their more massive cousins (Brinchmann et al. 2004; Bauer et al. 2005; Noeske et al. 2007; Feulner et al. 2005).

There are two important parts of this empirical picture that require clarification. First, many studies use SFR indicators that are highly susceptible to dust extinction (e.g., [O II] or UV-optical SED-derived SFRs; Cowie et al., 1996; Juneau et al. 2005; Bauer et al. 2005; Feulner et al. 2005). Second, all studies to date have relied on individual detections to allow SFR derivation. Neglecting SFR contributions from galaxies with individually undetectable star formation tracers biases the census of SFR at all masses. However, the bias is especially severe at low masses where the SFR limiting sensitivity implies that all low-mass galaxies with individual SFR detections have extremely high SSFR.

In this Letter, we present an analysis of Spitzer 24 μm observations of two COMBO-17 fields designed to circumvent these two key limitations. We estimate SFR by combining indicators of obscured and unobscured star formation, and attempt to derive average SFRs through stacking of galaxy subsamples with individually undetected SFR indicators. In § 2, we summarize the data and galaxy samples. In § 3, we describe our SFR measurements. In § 4, we present the contribution of different bins in stellar mass to the cosmic SFR and present the evolution of the SSFR with look-back time, again as a function of stellar mass. We discuss our results in § 5. We adopt a cosmology with H0 = 70 km s⁻¹ Mpc⁻¹, Ωm = 0.3, and ΩΛ = 0.7.

2. THE DATA AND GALAXY SAMPLES

The COMBO-17 survey (Wolf et al. 2003) has imaged three 30' × 30' fields in five broad and 12 intermediate optical bands from 350 to 930 nm with the goal of deriving high-quality photometric redshifts for >10,000 galaxies with mB < 24 mag in each field. The rest-frame luminosities in the U, B, and V bands and a synthetic UV2800 band centered at 280 nm have been derived for all COMBO-17 galaxies with photometric redshifts. By fitting the COMBO-17 multiband photometry with a library of spectral energy distribution (SED) templates, Borch et al. (2006) estimated the galaxies’ stellar mass-to-light ratio (M/L), and hence stellar mass for all mB < 24 galaxies, based on a Kroupa et al. (1993) initial mass function (IMF; such an IMF has stellar masses similar to within 10% compared to those derived using a Chabrier 2003 or Kroupa 2001 IMF). From these data, Borch et al. (2006) constructed stellar mass functions in four even redshift slices between z = 0.2 and z = 1.
Two of three COMBO-17 fields, the extended Chandra Deep Field–South (CDF-S) and the Abell 901/902 (A901) have been observed by the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) at 24 μm. The reduced 24 μm images cover an area of 1′ × 0′.75 around the CDF-S (Papovich et al. 2004) and of 30′ × 55′ in the A901 field (Bell et al. 2007). Both images have a pixel scale of 1′25 pixel−1 and a point-spread function (PSF) with full width at half-maximum (FWHM) of ≈6′. The IRAF/DAOPHOT package and empirically determined PSFs are used to simultaneously fit multiple sources to the 24 μm images and derive the total flux for each detected object to a depth of 83 μJy at the 5 σ level (to a completeness of 80%; see also Papovich et al. 2004 for details of data reduction, source detection, and photometry). To match these 24 μm catalogs to the COMBO-17 galaxy samples, a position tolerance of 2″ is adopted. If more than one galaxy exist within the tolerance, the nearest one is selected. The overlap area between COMBO-17 and MIPS imaging contains 9785 and 12,995 galaxies at $m_R < 24$ in the CDF-S (∼800 arcmin²) and the A901 field (∼850 arcmin²), respectively. Of them, 1735 (1872) are individually detected at 24 μm in the CDF-S (A901) field. Of the 6893 (8184) galaxies, 1201 (1461) have multiple (mostly two) COMBO-17 galaxies within the tolerance. We select galaxies with stellar mass $M_∗ > 10^9 M_☉$ in the redshift range 0.2 $< z < 1$, resulting in a sample of 6893 (8184) galaxies in the CDF-S (A901) field. Of the 6893 (8184) galaxies, 1201 (1250) are individually detected at 24 μm. The average 24 μm flux of the galaxies individually undetected by MIPS will be estimated by stacking, as described in the next section. The samples are complete at a mass limit ∼1, 1.8, 3, and $6 \times 10^{10} M_☉$ for redshift $z \sim 0.3, 0.5, 0.7$, and 0.9, respectively (Borch et al. 2006).

Owing to mismatches in depth between wide-area IR surveys (i.e., IRAS) and well-characterized optical galaxy surveys (i.e., the SDSS and 2dFGRS), it is challenging to produce an appropriate and well-defined local comparison sample. We have attempted to produce an adequate local control sample by collecting a sample of 2177 galaxies from the NASA/IPAC Extragalactic Database (NED) with 2MASS K-band magnitude $K < 12$ in the volume of 1500 $< cz/(\text{km s}^{-1}) < 3000$ and Galactic latitude $b > 30°$. Assuming a K-band $M/L$ of 0.6 $M_☉/L_☉$ and a Kroupa IMF, stellar masses were derived from the K-band absolute magnitude. The SFR is estimated from the total IR luminosity, as determined from IRAS observations. The local sample is not a complete volume-limited sample. However, we estimate that above $M_∗ > 10^{10} M_☉$, the sample is ∼65% complete, with an incompleteness that is largely geometric in origin (because some areas of the sky were not spectroscopically surveyed as thoroughly as others). If indeed the incompleteness is primarily geometric in origin, the average SFRs at a given stellar mass should not be biased.3 See Bell et al. (2005) for more details about the local sample selection and completeness.

3. SFR DETERMINATION

We split the sample galaxies into four redshift slices evenly covering the range from $z = 0.2$ to $z = 1$. In each redshift slice, sample galaxies are divided into five stellar mass bins: four bins with a bin width of 0.5 dex spanning from $M_∗ = 10^9$ to $10^{11} M_☉$, and one bin for $M_∗ > 10^{11} M_☉$. Each subsample of galaxies defined by optical data contains individually detected and individually undetected objects at 24 μm. Following Zheng et al. (2006), we estimated the total 24 μm flux for the subsample of individually undetected objects through stacking. The total 24 μm flux of the subsample is then obtained by adding the individual fluxes from the detected objects and the stacked flux from the individually undetected objects. Our SFR indicator, the total IR luminosity (8–1000 μm), is extrapolated from the 24 μm luminosity using three sets of local IR SED templates from Chary & Elbaz (2001), Dale & Helou (2002), and Lagache et al. (2004). In Zheng et al. (2007), we use stacking of IR-bright galaxies with 0.6 $< z < 0.8$ at 70 and 160 μm to show that the average IR SED of an IR-bright galaxy is spanned by these local template sets, lending credibility to the total IR luminosity estimated here to within a factor of 2.

We use the bolometric luminosity produced by young stars (UV+IR) to estimate the SFR, a procedure that accounts for both obscured and unobscured star formation. The total UV luminosity (1216–3000 Å) is estimated from the COMBO-17 2800 Å rest-frame luminosity $L_{UV, 2800}$ as $L_{UV} = 1.56 L_{2800}$. We used the conversion from Bell et al. (2005) to convert the UV+IR into the SFR. The SFR is calibrated to a Chabrier (2003) IMF. Using the sum of stellar masses for each subsample from Borch et al. (2006), we calculated the average SSFR, i.e., <$\text{SFR}$/<$\text{M}_∗>$, for all redshift and stellar mass bins. Formal uncertainties were estimated from bootstrapping. For each redshift and stellar mass bin, the average between the CDF-S and A901 was taken as the final result; the difference between the two is taken as a measure of field-to-field variance and included into the uncertainties. The estimates of both SFRs and stellar masses are affected by systematic errors, which other studies have estimated to be ≤0.3 dex. These systematic uncertainties are not included in our error bars but are substantially smaller than the dynamic range of the trends discussed in this Letter. Due to the COMBO-17 R-ball selection ($m_R < 24$), our sample galaxies are incomplete for low-mass bins at $z > 0.4$, where low-mass red galaxies with little blue radiation from newly formed stars fail to make the R-band selection cut but where low-mass blue galaxies containing more ongoing star formation remain available for the selection. The selection effect may lead to a potential overestimate of the SSFR for these incomplete bins. The SSFR at $z \sim 0$ was estimated using the local sample only for three high-mass bins where the sample is representative.

4. <$\text{SFR}$> (z) AS A FUNCTION OF GALAXY STELLAR MASS

In the previous section, we have determined the average SFRs for galaxies split into stellar mass and redshift bins. In order to determine the contribution of different stellar mass bins to the cosmic (average) SFR, we must combine the average SFRs at a given mass with the space density of galaxies in that same mass range, as a function of redshift. For this purpose, we adopt the stellar mass functions of Borch et al. (2006) for $0.2 < z < 1$ and Bell et al. (2003) for $z > 0$, although the results are unaffected to within the uncertainties if we adopt stellar mass functions from, e.g., Drory et al. (2004), Fontana et al. (2006), or Bundy et al. (2006) instead. We calculate the volume-averaged SFR over the redshift range $0 < z < 1$ for three galaxy stellar mass bins: $M_*/M_☉ > 10^{11}$, $10^{10}–10^{11}$, and $10^{9}–10^{10}$. The stellar mass functions from Borch et al. (2006) are derived from ∼25,000 COMBO-17 galaxies selected from three separate 30′ × 30′ fields. Therefore, the field-to-field variance is somewhat suppressed in this way (as one can see from comparison of the total SFR, derived from two COMBO-17 fields by Bell et al. 2007, to the smooth trends followed by our mass-binned cosmic SFRs). The local data point is not available for the stellar mass bin $10^9 < M_*/M_☉ \leq 10^{10}$.

3 At any rate, inspection of Figs. 1 and 2 shows that none of our conclusions actually depend on the $z \sim 0$ data; the purpose of its inclusion is simply to extend the trends to $z \sim 0$. 
The results are listed in Table 1 and shown in Figure 1, along with current measurements of the cosmic SFR density available in the literature (Hopkins 2004). Bell et al. (2007) constructed SFR functions using the same data sets and SFR estimator (UV+IR) as adopted here. The data points given by their SFR functions are also shown in this plot. Our estimate of the cosmic SFR density, i.e., the sum of the volume-averaged SFRs from the three stellar mass bins (contribution from galaxies of stellar mass <10^10 \ M_\odot is negligible), is in good agreement with Bell et al. (2007) and with other measurements from the literature.

Figure 1 shows that the volume-averaged SFR of galaxies in each of the three stellar mass bins decreases toward the present day with an indistinguishably similar slope since z = 1. In other words, the contributions to the cosmic SFR density from galaxies of different stellar mass ranges has not changed with cosmic epoch during the last 8 Gyr. Galaxies in the 10^{10} < M_\ast / M_\odot \leq 10^{11} range contain the bulk of the overall star formation at all cosmic epochs that we have examined. These galaxies also dominate the cosmic stellar mass density (Borch et al. 2006). A smaller part of the overall star formation takes place in galaxies with 10^{11} < M_\ast / M_\odot \leq 10^{12}. Relatively little star formation is associated with massive galaxies with M_\ast > 10^{11} \ M_\odot.

Figure 2 presents our measurements of the SSFR, i.e., SFR per unit stellar mass. Data points of the same redshift delineate the SSFR as a function of redshift, showing the redshift evolution of the SSFR.

Data points of the same redshift delineate the SSFR as a function of stellar mass. Those enclosed in the shaded region are in bins affected by serious incompleteness due to the COMBO-17 flux limit. For comparison, we overplotted the average SSFR for all galaxies, i.e., the ratio of the cosmic SFR density to the cosmic stellar mass density, calculated using Hopkins (2004) and Borch et al. (2006). As shown in Figure 2, the average SSFR for a galaxy stellar mass bin increases rapidly with redshift, in qualitative agreement with previous studies (e.g., Bauer et al. 2005; Feulner et al. 2005). Compared to our results, SFR estimates from rest-frame UV luminosity (the open symbols in Fig. 2; Feulner et al. 2005) produce lower SSFRs for high-mass galaxies and higher SSFRs for low-mass galaxies due to the reasons mentioned in § 1.

Yet, the change in SSFR is nearly equally strong for all galaxy mass bins. At all redshifts, the population-averaged SSFR of less massive galaxies is higher than that of more massive galaxies. Note that, as expected, galaxies of stellar mass around 10^{10.5} < M_\ast / M_\odot \leq 10^{11} have an SSFR comparable to the “cosmic average” SSFR, as they contribute most to both the cosmic average SFR and the stellar mass budget.

5. DISCUSSION AND SUMMARY

We combine Spitzer 24 μm observations with COMBO-17 data to explore the evidence for the “downsizing” of the star

| Table 1
| The Cosmic Star Formation History Split by Galaxy Stellar Mass |
| \( \log (\rho_{\text{SFR}}/M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}) \) |
| \( z \) | \( 10^{9} < M_\ast / M_\odot \leq 10^{10} \) | \( 10^{10} < M_\ast / M_\odot \leq 10^{11} \) | \( M_\ast / M_\odot > 10^{11} \) |
| ~0.1 | -2.6 \pm 0.1 | -3.0 \pm 0.1 |
| 0.2–0.4 | -2.2 \pm 0.1 | -2.7 \pm 0.1 |
| 0.4–0.6 | -1.9 \pm 0.1 | -2.4 \pm 0.1 |
| 0.5–0.8 | -1.7 \pm 0.1 | -2.5 \pm 0.1 |
| 0.8–1.0 | -1.6 \pm 0.1 | -2.4 \pm 0.1 |

Fig. 1.—Volume-averaged SFRs as functions of redshift, for galaxy samples of differing mean stellar masses. The average SFR is derived from the average bolometric luminosity (UV+IR) for galaxy subsets limited in mass and redshift. The data points in the hatched region are incomplete due to the COMBO-17 source selection (m_b < 24). The shaded region illuminates the cosmic SFR, i.e., the ratio of the cosmic SFR density to the cosmic stellar mass density, following Hopkins (2004) and Borch et al. (2006). Local data points are estimated for three high-mass bins using a local galaxy sample with near-IR and IRAS observations. The error bar represents the typical uncertainty of our SFR determinations. The dark gray dashed line is the SSFR required to double the mass of a galaxy by the present day. Data points above the mass-doubling line represent galaxies in intense star formation mode, and those below the line represent galaxies in quiescent star formation mode. For all galaxy subsamples of different stellar masses, the SSFR increases with redshift out to z ~ 1. At all redshifts, more massive galaxies always have lower SSFRs than less massive galaxies. These relations delineate a picture in which lower mass galaxies transition from an intense star formation phase into a quiescent star formation phase since z ~ 1, whereas most massive galaxies have formed stars quiescently across this epoch. Open symbols show results from Feulner et al. (2005) based on the SFR indicator rest-frame UV luminosity for stellar mass bins (converted to a Kroupa IMF) 10^{10.5} < M_\ast / M_\odot < 10^{11} (squares), 10^{11} < M_\ast / M_\odot < 10^{11.5} (triangles), and 10^{11.5} < M_\ast / M_\odot < 10^{12} (circles).
formation activity since $z \sim 1$. Specifically, we estimate the SFR from the UV (for unobscured star formation) and IR luminosities (for obscured star formation) for a sample of $\sim 15,000$ galaxies selected from the CDF-S and A901 fields. Through image stacking, we account for the SFR contributions of otherwise undetectable galaxies. Our measurements of the average SFR for galaxy subsets limited in mass and redshift account for contributions from both star-forming galaxies and quiescent galaxies in each subset. We find that the relative drop in SFR from $z \sim 1$ to the present day is nearly identical for different subsamples that span a range of $\sim 100$ in stellar mass. That is, all galaxy samples, independent of mass, exhibit the same gradual decline of star formation (and specific star formation) over the last 8 Gyr. At all redshifts, we find that high-mass galaxies have a substantially lower SSFR than their low-mass cousins.

While many of the qualitative features of this Letter have been understood for some time (e.g., Brinchmann & Ellis 2000; Bower et al. 2005; Juneau et al. 2005), this Letter quantifies the relationships between SSFR, galaxy stellar mass, and redshift. “Archeological” downsizing—that the stars in massive galaxies formed at earlier times than the stars in low-mass galaxies—is clearly recovered in this Letter, in Figure 2. On average, low-mass galaxies have SSFRs capable of more than $10^{-10}$ $M_\odot$ yr$^{-1}$, whereas galaxies with $M_\ast > 10^{11}$ $M_\odot$ are not capable of such growth at $z \leq 1$ in situ star formation alone.

Arguably the most striking and new contribution of this Letter is that the decline in SFR from $z \sim 1$ to the present occurs at the same rate in galaxies of all masses. A number of mechanisms have been postulated to drive the demise of star formation since $z \sim 1$: AGN feedback, the declining galaxy merger rate, gas consumption, changes in the availability of cooling or infalling fresh gas, and a host of other possibilities. We speculate that the declining supply of new gas falling in from the cosmic web at $z \leq 1$ seems an attractive candidate for driving much of the phenomenon that we observe (Noeske et al. 2007). The roughly constant rate of decline of SFR and SSFR for galaxies of widely differing masses is in contrast to the predictions of theoretical models in which cooling and hence star formation are quenched by heating due to radio-loud AGNs (e.g., Croton et al. 2006; Bower et al. 2006; but see also Neistein et al. 2006). This process is more important in massive galaxies for two reasons. First, more massive galaxies are more likely to host massive black holes, and more massive black holes are generally assumed to be capable of producing more energy and stronger heating. Second, it is generally assumed in such models that AGNs can only heat gas that is cooling from a quasi-hydrostatic hot halo, which form in large mass halos ($M_{\text{halo}} \gg 10^{12} M_\odot$) as opposed to the “cold mode” flows that are dominant in lower mass halos. For example, the models of Bower et al. (2006) predict a decline of a factor of $\sim 8$ from $z \sim 1$ to the present, in the SFR contributed by galaxies more massive than $10^{10.8} M_\odot$ (see their Fig. 8), while the SFR contributed by less massive galaxies declines by a factor of about 2–4 over this same interval. We find, using an independent model with “radio-mode” heating by AGNs (R. Somerville et al. 2007, in preparation), that the SFR in galaxies with stellar mass greater than $10^{11} M_\odot$ has declined by a factor of $\sim 15$ since $z \sim 1$, while the SSFR in the lower mass bins (the same bins used here) declines by only a factor of 3–5. The precise rate of decline of the SFR as a function of galaxy mass is no doubt sensitive to the details of the physics of star formation, but the prediction of a strongly differential “quenching” of star formation by AGN feedback in the form of radio heating, as it is currently implemented, seems inevitable. Our results therefore suggest that radio-mode heating by AGNs is not the dominant mechanism responsible for the decrease in the cosmic SFR from $z \sim 1$ to the present.

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