SPECIFIC STAR FORMATION RATES

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Abstract
We present results from a study to determine how star formation contributes to galaxy growth since redshift $z = 1.5$. Using galaxies from the MUnich Near-Infrared Cluster Survey (MUNICS) and the FORS Deep Field (FDF), we investigate the specific star formation rate (SSFR, star formation rate [SFR] per unit galaxy stellar mass) as a function of galaxy stellar mass and redshift. We test the compatibility of our results with a sample drawn from a larger volume using the Sloan Digital Sky Survey. We find that the SSFR decreases as galaxy stellar mass increases, suggesting that star formation contributes more to the growth of low-mass galaxies than high-mass galaxies at all redshifts in this study. We also find a ridge in the SSFR that runs parallel to lines of constant SFR and decreases by a factor of 10 from $z = 1$ to today, matching the results of the evolution in SFR density seen in the “Lilly-Madau” diagram. The ridge evolves independently of galaxy stellar mass to a particular turnover mass at the high mass end. Galaxies above the turnover mass show a sharp decrease in SSFR compared to the average at that epoch, and the turnover mass increases with redshift.

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Introduction
In an effort to study galaxy assembly, we look at the contribution of star formation (SF) to the growth of stellar mass in galaxies as a function of time. Stellar mass functions reveal that 50% of the local stellar mass density was in place by $z = 1$ (Drory et al. 2005). The stellar mass function describes the build up of stellar mass over cosmic time, but does not identify possible causes of growth for individual galaxies: mergers, tidal interactions, internal star formation, etc.

The well known “Lilly-Madau” diagram shows the star formation rate (SFR) density decreasing by a factor of 10 since $z = 1$ (Madau et al. 1996, Lilly et al. 1996), a result similarly concluded by measurements from SFR indicators covering nearly the full electromagnetic spectrum (e.g. Perez-Gonzalez et al.
2005). These results, however, give no indication of where the SF is taking place. Do all galaxies experience a factor of ten decrease in SFR? Is this trend dominated by high mass galaxies ending SF or by low mass galaxies initiating large amounts of efficient SF? How and where are half of the local stars formed while the global SFR is decreasing by a factor of 10?

Cowie et al. (1996) used rest-frame $K$-band (2.2$\mu$m) luminosities and [OII] $\lambda3727$ equivalent widths to show that galaxies with rapid SF decrease in $K$ luminosity, and therefore mass, with decreasing redshift. A more direct measure of this association is the specific star formation rate (SSFR, Guzman et al. 1997, Brinchmann & Ellis 2000), which measures the SFR per unit galaxy stellar mass, to study explicitly how SF contributes to galaxy growth for galaxies of different masses at different times in the history of the universe.

We combine two complementary redshift surveys to broaden the mass and redshift range that we can probe. The wide-area, medium deep MUNICS (Drory et al. 2001, Feulner et al. 2003) spectroscopic dataset provides intermediate to high mass galaxies typically in the mass range of $M_* \geq 10^{10}M_\odot$. The FORS Deep Field (Heidt et al. 2003, Noll et al. 2004) covers a small portion of the sky very deeply, contributing $M_* < 10^{10} M_\odot$ galaxies to the sample.

We adopt an $\Omega_M = 0.3, \Omega_\Lambda = 0.7, H_0 = 72$ km s$^{-1}$Mpc$^{-1}$ cosmology.

The Galaxy Data

The galaxies used in this study are gathered from the MUnich Near-Infrared Cluster Survey (MUNICS; Drory et al. 2001; Feulner et al. 2003) and the FORS Deep Field (FDF; Heidt et al. 2003; Noll et al. 2004). The MUNICS project is a wide-area, medium-deep, photometric and spectroscopic survey selected in the $K$-band, reaching $K \sim 19.5$, and including $BVRIZK$. Spectroscopy is complete to $K \sim 17.5$ over 0.25 square degrees and reaches $K = 19.5$ for 100 square arcmins. The spectra cover a wide wavelength range of 4000 – 8500 A at 13.2 A (FWHM) resolution, sampling galaxies in the redshift range of 0.07 < $z$ < 1. Our MUNICS sample contains 202 objects, which are mostly massive ($M_* > 10^{10} M_\odot$) field galaxies with detectable [OII]$\lambda3727$ emission.

The FORS Deep Field (FDF) spectroscopic survey provides low-resolution spectra with detectable [OII]$\lambda3727$ in the spectral window (3300 – 10000 A at 23 A (FWHM) resolution) to $z = 1.5$. The FDF survey is $I$-band selected reaching $I_{AB} = 26.8$ with spectroscopy to $I_{AB} = 24$. The FDF covers 7' x 7' in eight bands: $UBgRIzJK$. Our FDF sample includes 152 galaxies with detectable SF; and masses of mostly $M_* < 10^{10} M_\odot$.

The trends seen among the FDF and MUNICS galaxy surveys exhibit similar evolution in their overlapping mass range around $M_* = 10^{10} M_\odot$ and
are therefore suitable to analyze simultaneously to cover such a large range of galaxy stellar mass.

We developed an automated spectral measurement routine to consistently determine the fluxes of emission lines. We use the flux of the [OII] $\lambda 3727$ emission feature, which remains in the spectral window to $z = 1.5$, as a SFR indicator. We use the Kennicutt (1998, Equation 3) conversion from [OII] line luminosity to SFR in units of solar masses per year.

Stellar masses are determined for each galaxy by fitting a grid of composite stellar population models of varying age, star formation history, and dust extinction to multi-wavelength photometry to determine individual mass-to-light ($M/L$) ratios. This process is described in detail in Drory et al. (2004a).

### Specific Star Formation Rates

Redshift and SFR distributions for both samples can be found in Figure 1 of Bauer et al. (2005). The majority of galaxies in the full samples (52% for MUNICS and 80% for FDF) have detectable SF, via the [OII]$\lambda 3727$ emission feature, and the closely matching redshift distributions indicating little redshift bias in sample selection. The maximum SFR increases with redshift, and is consistent between the two samples.

Fig. 1 shows the SSFR versus galaxy stellar mass as a function of redshift, to $z = 1.5$. The open squares show MUNICS galaxies, the closed squares are FDF galaxies and the crosses in the lowest redshift bin are SDSS galaxies to be discussed in more detail later. Galaxies of low to intermediate stellar mass form a “ridge” in SSFR running parallel to lines of constant SFR in each redshift bin. The ridge exists in all redshift bins until, at some high “turnover” mass, the SSFRs drastically decrease, as expected for the higher mass, early-type, redder galaxies which tend to form fewer stars after $z = 1$. The turnover mass increases with redshift, showing higher SSFR for higher mass galaxies at earlier times, a process termed “downsizing” by Cowie et al. (1996).

A correlation exists between SSFR and mass (e.g. Brinchmann & Ellis 2000). Here we show this correlation evolves with redshift up to $z = 1.5$ independently of galaxy stellar mass. The ridge in the SSFR shifts downward as redshift decreases, indicating a steady decrease in the global SFR, from $10 M_\odot$yr$^{-1}$ at $z = 1.5$ to $1 M_\odot$yr$^{-1}$ at $z = 0$, agreeing with concurring trends in the “Lilly-Madau” diagram (Madau et al. 1996, Lilly et al. 1996) determined from a large variety of SFR indicators (see compilation by Hopkins 2004). Similar trends are also identified in the large sample of Feulner et al. (2005). While detecting the lowest SFRs at any epoch is affected by incompleteness, the evolution of the upper envelop is independent of selection effects.

In the present study we apply no corrections for extinction to the [OII] emission line fluxes. For the 10% of the galaxies where we have the necessary
Figure 1. Specific Star Formation Rates versus Galaxy Stellar Mass. The open squares are MUNICS galaxies, filled squares represent FDF galaxies, the crosses show SDSS galaxies chosen to match the photometric limits of the MUNICS sample, and the triangles show 1σ upper limits for SSFR. The solid diagonal line identifies a constant SFR = 1 M⊙ yr⁻¹. The dotted lines show the mass limits (vertical) and detectable star formation limits for the MUNICS survey while the dashed lines show the lower limits for detectable SSFR for FDF, derived from the spectroscopic sensitivity limits. Estimated error bars, appropriate for the majority of galaxies are shown in the 0.4 < z < 0.7 bin.

Balmer emission lines to perform a proper dust correction, we find an average $E(B-V) = 0.2$, assuming a case B recombination. We feel it necessary to apply a unique dust correction to each galaxy (Maier et al. 2005) and consider a flat correction determined from a small sample of low redshift galaxies irrelevant to the differential SF studied here.

To ensure that the increase in SSFR at higher redshifts is not due to rarer objects being seen as larger volumes are probed, we investigate the trends in SSFR from the SDSS. We collected SDSS galaxies (Abazajian et al. 2004) selected to match the MUNICS magnitude limits as described in (Drory et al. 2004b), and determined stellar masses in the same way as the rest of our
Specific Star Formation Rates

sample. We used the reported [OII]λ3727 emission line flux from the SDSS and followed the same Kennicutt (1998) conversion to SFR.

We chose a random sample of SDSS galaxies to match the number of galaxies in the lowest redshift bin from MUNICS and FDF and show them in Fig. 1 as crosses. The consistent SSFR between all galaxies samples, confirmed by choosing several sets of SDSS galaxies, shows that our results are not due to volume effects in the low redshift bin.

Discussion

We present a study of the contribution of star formation (SF) to the growth of stellar mass in galaxies since \( z = 1.5 \) showing the SSFR versus galaxy stellar mass as a function of redshift over five decades in galaxy stellar mass. At all redshifts, the SSFR decreases as stellar mass increases. This indicates a higher contribution of SF to the growth of low mass galaxies since \( z = 1.5 \) and suggests that high mass galaxies formed the bulk of their stellar content earlier than \( z = 1 \).

Fig. 1 shows evidence of a ridge in SSFR that runs parallel to lines of constant SFR. The ridge exists for all galaxy stellar masses \( M_*=10^7 - 10^{11}M_\odot \) and increases uniformly, independent of mass as redshift increases. The first evidence for such a ridge and an upper bound in SSFR, moving to higher SFRs with increasing redshift was noted by Brinchmann & Ellis (2000). Our work moves beyond that study with spectroscopy of a mass limited sample at each redshift bin, covering a wide range of masses (Bauer et al. 2005).

Galaxies exist on Fig. 1 only when the SF induces detectable amounts of [OII] λ3727 emission. Our mass-selected galaxy samples, while not biased towards identifying star-forming galaxies, still show detectable SF in a majority (50 – 80%) of the galaxies at any epoch. Many studies focus on disentangling different stages in the lifetimes of individual galaxies. While this remains a difficult task, common trends in evolutionary paths have identified stages where detectable star formation occurs. One such stage is represented by a population of highly star forming, dust enshrouded, luminous IR galaxies (LIRGs) which are known to be much more common at \( z > 1 \) than they are today (e.g. Flores et al. 1999, Perez-Gonzalez et al. 2005). It is most likely that LIRGs correspond to short bursts of intense SF induced by recent merging or gas infall (Hammer et al. 2005). These brief bursts represent only occasional phases and not normal stages of SF in galaxy lifetimes, and we could possibly be detecting the low mass galaxies during LIRG phases.

The first studies of the evolution of the SFR from Spitzer Space Telescope 24 μm data have recently been published (Bell et al. 2005, Perez-Gonzalez et al. 2005). The SSFR evolution with stellar mass and redshift largely agrees with the work presented here for the low to intermediate mass galaxies, but
show more scatter towards higher SSFRs in the high mass regime. While thermal IR observations detect the highly dust obscured objects missed by optical- and NIR-selected samples, a large uncertainty remains in converting the observed light into the total IR flux. The amount of dust heated by old stars is unknown. Since the most massive galaxies contain the largest populations of old stars locally (e.g. Kennicutt et al. 1994) and at high redshifts (Drory et al. 2005), there is a possible tendency to overestimate the IR-derived SFR at higher stellar masses.

Large new surveys greatly improve our working understanding of galaxy evolution and stellar mass build up in the universe, but many uncertainties persist while we seek to understand the contributing components of new data. It remains important to continue multiwavelength studies of galaxy evolution in seeking concordance among various methodologies.

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