Which galaxies contribute to the SFRD over the past 8 Gyrs?

The dependence of star formation activity on stellar mass surface density and Sersic index in zCOSMOS galaxies at $0.5<z<0.9$ compared with SDSS galaxies at $0.04<z<0.08$


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Introduction

- What physical processes inside galaxies drive the changes in the SFRs in individual galaxies that, taken together, produce the large decline in the SFRD since $z \sim 2$?

- Studies at intermediate redshifts of the SFR or specific SFR (e.g. Bundy et al. 2006, Noeske et al. 2007) did not use information on the internal structure properties of galaxies.

- Studies using the SDSS have argued that the surface mass density may be more important than stellar mass in regulating star formation.

- This study: use SFRs derived from emission lines, carefully construct compatible mass-complete subsamples of both zCOSMOS and SDSS, compute half-light radii in a consistent way, at the same rest-frame wavelength, and explore contributions of galaxies with different Sersic indices to the overall SSFR-$\Sigma_M$ relation.
Introduction (2)

- The behaviour of the SSFR of local SDSS galaxies with $\Sigma_M$ follows a smoothed “step” function dropping substantially at a characteristic $\Sigma_{M\text{char}}$
- Brinchmann et. al (2004): a low SSFR peak is more prominent at high surface mass density $\log \mu^*$ ($\log \Sigma_M$) than at high stellar mass $\rightarrow$ surface mass density may be more important than stellar mass in regulating star formation

- Goal: do a comparative study of the dependence of specific SFR (SSFR) on average surface mass densities ($\Sigma_M$) in zCOSMOS and SDSS to obtain clues about the links between the internal evolution of galaxies, in particular the build-up of stellar mass, and the global changes that are seen in the population of galaxies as a whole

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Derivation of stellar masses

• Stellar masses must be derived from estimating the M/L ratio of the stellar population using multi-band photometry using the widest possible wavelength range. Unfortunately, while such data exist in the COSMOS field, systematic near-infrared photometry is not yet available for the SDSS.

• To achieve the highest possible internal consistency, we derive zCOSMOS mass estimates from rest-frame optical colors, for both SDSS and zCOSMOS, using the relation between rest-frame U-B and B-V colors and M/L used in DEEP2 studies (Lin et al. 2007), relation which corrects M/L for the galaxy redshift and evolution in color → good agreement with COSMOS SED masses (left panel)

• Slight increase in $\Sigma_M$ with stellar mass, but with a large scatter
The so-called Sersic profile is adopted to describe the radial surface brightness dependence of galaxies. zCOSMOS: we fit the distribution of light within an elliptical area (ellipticity $e=1-b/a$) to half-light radii $R_{1/2}$ (semi-major axis of the ellipse containing half of the total flux) and Sersic indices $n$ (Sargent et al. 2007).

\[
\Sigma(r) = \Sigma(R_{1/2}) \exp \left\{-k \left[ \left( \frac{r}{R_{1/2}} \right)^{1/n} - 1 \right] \right\}
\]

Top panel: Sersic surface brightness profiles for $n=0.5, 1, 2, 4, 10$: at larger $n$ (early-type galaxies) profiles are steep at small radii and then flatten out as $R$ increases, while profiles with small $n$ (disk galaxies) are shallow at small sizes and drop rapidly with increasing $R$.

Surface mass density (stellar mass per unit area):
\[
\log(\Sigma_M/M_{\text{sun}}/\text{kpc}^2) = \log(M/M_{\text{sun}}) - \log[2\pi b/a(r_{1/2}/\text{kpc})^2]
\]
Examples of ACS images with small/large n and b/a

Sersic index $n < 1.5$, axis ratio $b/a > 0.55$ (disk galaxies)

Sersic index $n < 1.5$, axis ratio $b/a < 0.55$ (more dust, inclined disk galaxies)

Sersic index $n > 2.5$, axis ratio $b/a > 0.55$ (early-type galaxies)

Sersic index $n > 2.5$, axis ratio $b/a < 0.55$ (objects with disks)
SFRs derivation for zCOSMOS galaxies at 0.5<z<0.9

- only stars with masses larger than 10$M_{\odot}$ (lifetimes < 20Myrs) contribute significantly to the ionizing flux, so the emission lines, which effectively re-emit this luminosity, provide a nearly instantaneous measure of the star formation rate (SFR), independent of the previous star formation history

- the conversion factor between ionizing flux and SFR is computed using evolutionary synthesis models (e.g. Kennicutt 1998)

- one of the best-understood SFR indicators is H$\alpha$: the H$\alpha$ extinction corrected luminosity is directly proportional to the hydrogen-ionizing radiation from massive stars

- drawback: H$\alpha$ is redshifted out of the optical window beyond z~0.5

- the [OII]$\lambda$3727 forbidden-line doublet is observed in the optical at 0.5<z<0.9 (look-back time 5Gyrs-7.5Gyrs), and calibrated (through H$\alpha$) as a SFR tracer

- we use the [OII]-SFR calibration by Moustakas et al. (2006), which takes dust extinction and metallicity into account, transforming the [OII] line luminosities in SFRs using a correction dependent on the galaxy’s restframe B-band magnitude
The 10k zCOSMOS-bright sample

- **zCOSMOS**: large redshift survey undertaken in the COSMOS field using 600 hours of observation with VIMOS at VLT

- **zCOSMOS-bright**: a magnitude limited I-band $I_{AB}<22.5$ sample of ~20000 galaxies at $0.1<z<1.2$ covering the 1.5 deg$^2$ COSMOS ACS field; 100km/s velocity accuracy using R~600 MR grism

- Analysis based on first 81 (of 180 masks) with 1 hour integration time of zCOSMOS-bright → contain about 10000 galaxies, the 10k zCOSMOS-sample

Distribution of objects in the 81 masks, due to the design of VIMOS (4 quadrants, each 7x8 arcmin$^2$ separated by a cross-shaped region 2 arcmin wide)
Mass completeness of the zCOSMOS sample

- Blue late-type (n<1.5) galaxies generally have a lower M/L. Therefore, in a given flux-limited sample like zCOSMOS and SDSS, they are detected at a given redshift to smaller masses than red early-type galaxies, simply because the latter are fainter at a given mass, i.e. have a higher M/L.

- In SDSS we can choose the redshift range (0.04<z<0.08) so that the SDSS sample is effectively complete for the masses of interest

- The current analysis is based on 648 galaxies with logM>10.4 at 0.5<z<0.7, and 520 objects with logM>10.7 at 0.7<z<0.9
Mass completeness of the zCOSMOS sample (2)

- We calculate the maximum M/L at a given redshift, i.e., that of a red passively evolving galaxy, and apply this to calculate the minimum mass that a galaxy must have to be brighter than $I_{AB}=22.5 \rightarrow$ all galaxies with masses above this mass limit will be visible in the survey (have lower M/L) \rightarrow magenta points give Bruzual & Charlot (2003) location of a model galaxy (using different star formation histories and ages of the model galaxy) with $I_{AB}=22.5$ at $z=0.7$ (left panel) and $z=0.9$ (right panel)

- Mass completeness shown by vertical thick green line (as the M/L asymptotes to a limiting value the locus of the magenta dots becomes vertical) : $\log M>10.4$ at $0.5<z<0.7$ (648 galaxies), $\log M>10.7$ at $0.7<z<0.9$ (520 galaxies)
Specific star formation rates (SSFRs) and downsizing

- Specific SFR vs. stellar mass as a function of Sersic indices for 3048 zCOSMOS galaxies at 0.5<z<0.9; the solid and dashed diagonal lines show SFR of 1 and 5 $M_{\odot}$/yr; $\text{Age}_{\text{Universe}}$: magenta dashed horizontal lines.
- SSFR is an indicator of the galaxy SF history, since $1/\text{SSFR} = \text{TSFR}$ is the time required for the galaxy to form all its stellar mass at the current SFR.
- Galaxies with different Sersic indices have different SFHs: most $n>2.5$ have $\text{T}_{\text{SFR}}>\text{Age}_{\text{Universe}}$ (quiescent, higher SFR in the past), and most $n<1.5$ objects have $\text{T}_{\text{SFR}}<\text{Age}_{\text{Universe}}$ (active galaxies, lower SFR in the past).
- Downsizing effect: higher number of galaxies in yellow hatched region at $z>0.7$. 

![Image](image_url)
SDSS SSFR vs. stellar surface mass density at 0.04<z<0.08

• Panels a+b: the median SDSS SSFR is almost independent of surface mass density for low $\Sigma_M$, and then abruptly changes at $\log\Sigma_{M\text{char}} \sim 8.5$, as seen also by Brinchmann et. al (2004), see panel (e)

• This characteristic step-function dependence is due to the change-over from disk-dominated ($n<1.5$, panel c) to bulge-dominated ($n>2.5$, panel d) galaxies as $\Sigma_M$ increases

• The fraction of $n>2.5$ SDSS objects shows a sharp increase at $\log\Sigma_{M\text{trans}} \sim 8.5$, the point where SSFR abruptly changes
The stellar – mass size relation: zCOSMOS vs. SDSS

• The distribution of sizes of SDSS galaxies is displaced to higher values at a given mass compared with zCOSMOS (panel a+b), and this is due to galaxies with \( n > 2.5 \) (panel d) → The average half-light radius of \( n > 2.5 \) objects is smaller by ~25% at \( z \approx 0.7 \) than at \( z \approx 0 \) consistent with theoretical predictions (Khochfar & Silk 2006, Naab et al. 2007, smooth envelope accretion by minor mergers scenario)

• There is little change in the mass-size relation for zCOSMOS compared to SDSS \( n < 1.5 \) (disk) galaxies (panel c)

Sersic index \( n < 1.5 \), axis ratio \( b/a > 0.55 \)

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Reliability of zCOSMOS stellar masses of n>2.5 objects

- Comparison of B-band M/L ratios for zCOSMOS galaxies with b/a>0.55 and n>2.5 with M/L ratios obtained using the stellar velocity dispersions and the fundamental plane for early-type (E+S0) galaxies by Treu et al. (2005)

- The slope of the observed mean zCOSMOS M/L - mass relation agrees with the slope of the local relation (solid diagonal line offset to lower M/L, as expected for a passively evolving population) → derived zCOSMOS stellar masses are reasonable.
zCOSMOS vs. SDSS: SSFR vs. $\Sigma_M$ at $z<0.7$

- The median SSFR - $\Sigma_M$ relation of zCOSMOS galaxies is similar to SDSS, but with median SSFR values being about 5-6 times higher than for SDSS
- The $\Sigma_{M\text{char}}$ “step” shifts by 0.1 - 0.2 dex in zCOSMOS relative to SDSS: explained by a modest differential evolution in the size - mass relation
- SSFR of $n<1.5$ galaxies declines rapidly → mass build-up is <30% between $z\sim0.7$ and $z\sim0$; additional flatness of mass-size relation → not much increase in size

- The cross-over point $\Sigma_{M\text{trans}}$ shifts to higher $\Sigma_M$, because the average $\Sigma_M$ of $n>2.5$ galaxies shifts to higher values at higher $z$
- ACS images: the upturn in the median SSFR for $n>2.5$ galaxies (panel d) is evidently due to galaxies with a significant disk component with Sersic index $n>2.5$ due to a large dominant bulge
zCOSMOS vs. SDSS: SSFR vs. $\Sigma_M$ a and mass vs. size at 0.7<z<0.9

- The behaviour of the SSFR vs. $\Sigma_M$ and mass vs. size relations for 0.7<z<0.9 galaxies compared to the logM>10.7 SDSS samples is similar to that of galaxies at the slightly lower redshift of 0.5<z<0.7

- However, the changes in sizes of early-type galaxies (n>2.5) becomes even more pronounced, leading to an increase in $\Sigma_{M_{\text{char}}}$

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Reliability of size measurements

• There is a good agreement between the sizes of zCOSMOS massive galaxies computed started from the circular Petrosian radius containing 50% of the Petrosian flux and applying Eq. (6) of Graham et al. (2005) and the sqrt(a/b) correction to compute semimajor half-light radii, and the sizes (semimajor axis) computed with GIM2D (right panel)
Summary and Conclusions

- Carefully constructed compatible mass-complete subsamples of both zCOSMOS and SDSS, computed half-light radii, masses and SFR in a consistent way, and explored contributions of galaxies with different Sersic indices to the overall SSFR - $\Sigma_M$ relation.

- There is evidence that, at all redshifts, the mean SSFR within a given population (either disk-dominated with $n<1.5$, or bulge-dominated with $n>2.5$) is independent of surface mass density.

- The observed SSFR – $\Sigma_M$ step-function relation is due, at all redshifts, to the changing mix of disk-dominated and bulge-dominated galaxies as surface density increases and the strong difference in the average SSFR between disks and bulges.

- The mean increase in SSFR by a factor of 5 - 6 back to $z \sim 0.7$ is independent of $\Sigma_M$ and also of Sersic index $n$. This increase matches that of the global star formation rate density ($SFRD$) of the Universe as a whole, suggesting that all types of galaxies are participating in the increase in SFR to these redshifts.