tracking the metamorphosis of galaxies through cosmic time

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Galaxy Growth in the Cosmic Web

dark matter halos form out of initial density perturbations
galaxies assemble their mass via accretion and mergers along cosmic web
stars form out of cooled accreted gas
star formation regulated by gas inflows/outflows/feedback
- stellar and supernova feedback (important at low mass)
- active galactic nuclei feedback (important at high mass)
- virial heating in massive halos

Illustris Simulation: dark matter [---] gas velocity
Galaxy Growth in the Cosmic Web

galaxy structure (size, bulge/disk)
~ assembly + star-formation history
smooth accretion
= high angular momentum, large disk

violent mergers/instabilities
= angular momentum loss,
  bulge formation;
correlated with black hole growth

environment/local density of galaxies:
increased merger activity;
destruction of low mass galaxies

EAGLE simulation
Cosmic Stellar Mass Density v. time

Figure 11
The evolution of the stellar mass density. The data points with symbols are given in Table 2. The solid line shows the global stellar mass density obtained by integrating the best-fit instantaneous star-formation rate density $\psi(z)$ (Equations 2 and 15) with a return fraction $R = 0.27$.

When needed, we have scaled from a Chabrier IMF to a Salpeter IMF by multiplying the stellar masses by a factor of 1.64 (Figure 4). At high redshift, authors often extrapolate their SMFs beyond the observed range by fitting a Schechter function. Stellar mass completeness at any given redshift is rarely as well defined as luminosity completeness, given the broad range of $M/L$ values that galaxies can exhibit. Unlike the LFs used for the SFRD calculations where we have tried to impose a consistent faint luminosity limit (relative to $L^*$) for integration, in most cases we have simply accepted whatever low-mass limits or integral values that the various authors reported.

Many authors found that the characteristic mass $M^*$ appears to change little for $0 < z < 3$ (e.g., Fontana et al. 2006, Ilbert et al. 2013) and is roughly $10^{11} M_\odot$ (Salpeter). Therefore, a low-mass integration limit similar to that which we used for the LFs ($L_{\text{min}} = 0.03 L^*$) would correspond to $M_{\text{min}} \approx 10^{9.5} M_\odot$ in that redshift range. A common but by no means universal low-mass integration limit used in the literature is $10^8 M_\odot$.

Generally, SMFs have flatter low-mass slopes than do UVLFs (and sometimes IRLFs), so the lower-mass limit makes less difference to the SMDs than it does to the SFRDs.

Our model predicts an SMD that is somewhat high ($\sim 0.2$ dex on average, or 60%) compared with many, but not all, of the data at $0 < z \lesssim 3$. At $0.2 < z < 2$, our model matches the SMD measurements for the Spitzer IRAC-selected sample of Arnouts et al. (2007), but several other modern measurements in this redshift range from COSMOS (Pozzetti et al. 2010, Ilbert et al. 2013, Muzzin et al. 2013) fall below our curve. Carried down to $z = 0$, our model is somewhat high compared with several, but not all (Gallazzi et al. 2008), local estimates of the SMD (e.g., Cole et al. 2001, Baldry et al. 2008, Li & White 2009).

Several previous analyses (Hopkins & Beacom 2006, but see the erratum; Hopkins & Beacom 2008; Wilkins et al. 2008a) have found that the instantaneous SFH overpredicts the SMD by larger factors, up to 0.6 dex at redshift 3. We find little evidence for such significant discrepancies, although there does appear to be a net offset over a broad redshift range. Although smaller, a $\sim 60\%$ effect should not be disregarded. One can imagine several possible causes for this discrepancy; we consider several of them here.

SFRs may be overestimated, particularly at high redshift during the peak era of galaxy growth. For UV-based measurements, a likely culprit may be the luminosity-weighted dust corrections.

~75% of cosmic stellar mass formed @ 1 < z < 6

~25% stellar mass formed at z<1

<1% of stellar mass formed during reionization

compilation from Madau & Dickinson 2014
Cosmic Star-Formation Rate v. time

peak of cosmic SFR $\approx z \sim 1-3$

compilation from Madau & Dickinson 2014
Star-Formation ~ Stellar Mass @ 0 < z < 6

SFR ~ stellar mass for star-forming galaxies at all redshifts?
SFR per unit stellar mass v. time

SFR/Mstar (sSFR) normalization evolves strongly with redshift

scatter in SFR-Mstar relation roughly constant with time

⇒ evolution NOT due to increased starburst (merger) fraction
Molecular Gas Fraction v. time

molecular gas fraction increases to $z \sim 3$

$sSFR \sim$ gas fraction

Saintonge et al. 2013; Daddi, Tacconi, Genzel, Scoville
the morphologies of galaxies

Hubble Classification Scheme

Galaxy bulge strength is strongly correlated with star-formation and stellar mass.

Wuyts et al. 2012
Star-Forming Gas-Rich Rotating Disks @ z~2

Wisnioski et al. 2015; Forster-Schreiber; Nelson

extended H-alpha disks
rotating disks with high gas dispersions
high turbulence?

clumps/irregular
in rest-frame UV/optical light
but smooth stellar mass maps

Wuyts et al. 2012; Guo et al. 2014; Elmegreen
Fading/Quenching Galaxies @ z~2

Massive red/quenched galaxies are bulge-dominated from 0 < z < 2.5

Quenching = Compact/Bulge Structure

Structure (bulge strength, compactness, central density) is a better predictor of quenching than stellar mass at z~2.

Red/Quenched Galaxies increase with time

red low sSFR massive galaxies appear at \( z > \sim 3 \);

increase in mass + number with time

(eg Whitaker et al.; Brammer et al; Brown et al; Faber et al; Bell et al)
Galaxy mergers can transform galaxies

- disk
- tidal tails
- disturbed
- bulge/spheroid

e.g. Cox et al. 2006, 2008; Jonsson et al. 2008; Lotz et al. 2008, 2010; Snyder, Lotz et al. 2015
Merger $\rightarrow$ Starburst $\rightarrow$ AGN $\rightarrow$ Spheroid ?
Galaxy Mergers are common

massive galaxies experience at least 1 major merger, and several minor mergers throughout their lifetime

major mergers were more frequent in the past* (observed to z~1)
tracking the metamorphosis of galaxies over past 10 billion years

$0 < z < 3$
HST WFC3/IR: distant galaxy structures

need high-spatial resolution NIR imaging to probe rest-frame optical structures at lookback times > 8 Gyr (z >1)

⇒ Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS) - PI S. Faber & H. Ferguson

HST WFC3 NIR imaging
wide fields: UDS, EGS, COSMOS, 1-orbit depth J + H, ~0.2 sq. degrees

deep fields: GOODS-N + S, ~4-orbit depth Y, J, H, ~0.04 sq. degrees
Fading/Quenching Galaxies over Cosmic Time

![Graph showing the relationship between stellar mass and SFR across different redshifts. The graph is split into three panels, each showing a different redshift range: $0.02 < z < 0.20$, $0.5 < z < 1.5$, and $1.5 < z < 2.5$. Each panel displays a scatter plot with galaxies marked by their SFR and mass, color-coded to indicate the median $n_{\text{Sersic}}$. The plots show a clear trend of increasing quiescence with lookback time.](image_url)

Cosmological hydro simulations (e.g. Illustris) can reproduce the modern Hubble sequence (z=0)

Data

Bulge strength

Wuyts et al. 2011

Theory

Snyder, Torrey, Lotz et al. 2015b
Cosmological hydro simulations (e.g. Illustris) can reproduce the modern Hubble sequence (z=0)

Data

Bulge strength

Theory

Wuyts et al. 2011

Snyder, Torrey, Lotz et al. 2015b
the metamorphosis of galaxies

10 Gyr ago

minor mergers?
newly quenched galaxies?
disk instabilities?
accretion?

interactions and mergers?

today
evolutionary paths of high-z galaxies

but structural evolution not always monotonic? simulated z~2.2 compact galaxies can develop star-forming disks triggered by accretion and/or gas-rich minor mergers?

evolutionary paths of high-z galaxies

Barro et al. 2014 (also Brennan et al 2015; Zoltov et al. 2015)
parametric morphology - Sersic index

\[ \Sigma(r) = \Sigma_e e^{-\kappa (r/r_e)^{1/n} - 1}, \]

Sersic 1968; Peng et al. 2002

Sersic fits miss detailed information (disturbances, star-forming clumps .. )
Lotz et al. 2004

Spheroids

more flux in fewer pixels

G

more uniform surface brightness

M_20

spatially extended

spatially concentrated

Mergers

Spheroids

Disks
Beyond the Hubble Sequence

non-parametric morphologies
G-M$_{20}$-C-A-MID ⇒
Principal Component Analysis
+ Hierarchical Group Finder ⇒
~8 unique “groups”

PC1 ~ G-M$_{20}$ bulge strength
PC2 ~ Concentration
PC3 ~ Asymmetry

CANDELS 1.4 < z < 2
rest-frame blue light

Peth, Lotz et al., 2016, in press
Beyond the Hubble Sequence

non-parametric morphologies
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PC1 ~ G-M$_{20}$ bulge strength

Peth, Lotz et al., 2016, in press
Quenching = Compact/Bulge Structure

Structure is a better predictor of quenching than stellar mass at z~2.

Growth of compact red galaxies at $z < 3$

massive red galaxies smaller at $z \sim 2-3$

grow via minor mergers at late times?

e.g. van der Wel et al. 2014

e.g. van Dokkum et al. 2015; Oser, Nipoti; Naab;
Evolution of Size-Mass Relation

Size (rest-frame blue light) vs Stellar Mass Density ($\rho (M_{\text{sun}} \text{Mpc}^{-3})$)

- ~ 6 Gyr ago
- ~ 7 Gyr ago
- ~ 8 Gyr ago
- ~ 9 Gyr ago
- ~ 10 Gyr ago
- ~ 11 Gyr ago

Lotz in prep, 2016
build up of massive, large galaxies

Stellar Mass

Stellar Mass Density ($\rho_{\text{star}}$ ($M_{\odot}$ Mpc$^{-3}$))

Lotz in prep, 2016
small galaxies quench first

Size (rest-frame blue light)

Stellar Mass

$\langle sSFR \rangle = \frac{\langle SFR \rangle}{\langle M_{\text{star}} \rangle}$

Lotz in prep, 2016
inferred ‘gas fraction’ (assume local SF - gas reln)

\[ \Delta (\text{lookback time}) \sim 1 \text{ Gyr} \]

\[ \langle f(\text{gas}) \rangle = \frac{\langle M_{\text{gas}} \rangle}{\langle M_{\text{gas}} + M_{\text{star}} \rangle} \]

Log Petrosian Radius (kpc)

Log Stellar Mass

Lotz in prep, 2016
central bulge formation proceeds quenching

Lotz in prep, 2016
central bulge formation proceeds quenching

~ 6 Gyr ago ~ 7 Gyr ago ~ 8 Gyr ago ~ 9 Gyr ago ~ 10 Gyr ago ~ 11 Gyr ago

Stellar Mass

<PC1> (~G-M\textsubscript{20} bulge strength)

Lotz in prep, 2016
central bulge formation proceeds quenching

$<\text{sSFR}> = <\text{SFR}>/<\text{Mstar}>$

Lotz in prep, 2016
disturbed galaxies are star-forming, large

Size (rest-frame blue light)

Stellar Mass

Lotz in prep, 2016

fraction of high PC3 galaxies (~Asymmetry/disturbance)
future quenched bulges are disturbed

Lotz in prep, 2016

Stellar Mass

~ 6 Gyr ago

~ 7 Gyr ago

~ 8 Gyr ago

~ 9 Gyr ago

~ 10 Gyr ago

~ 11 Gyr ago

disturbed

smooth

fraction of high PC3 galaxies

(~Asymmetry/disturbance)
the metamorphosis of galaxies: what we know

• SFR ~ stellar mass with little scatter over cosmic time  
  ⇒ few starbursts

• sSFR = SFR/stellar mass evolves strongly  
  ⇒ tied to increasing molecular gas fraction

• large star-forming disks at z~2 are clumpy and turbulent

• fading/quenching galaxies are bulge-dominated;  
  ⇒ structure is best predictor of quenching at z~2

• size-mass evolution:  
  smallest star-forming galaxies at a given mass quench first,  
  have lowest sSFR, gas fractions
the metamorphosis of galaxies: open questions

• Where are the z>1 galaxy mergers?

• sSFR ~ gas fraction ~ galaxy structure; Why? angular momentum ⇔ feedback ⇔ star-formation?

• How does feedback proceed on < 1 kpc scales? AGN or star-formation?
Why are early galaxies so small and dense, sometimes packing the entire mass of the Milky Way into less than 1/20 its volume? How are galactic disks assembled—through slow accretion of gas or through many mergers with smaller galaxies? What are the massive, unresolved clumps dominating early disks? Do they form bulges? And what causes galaxy quenching: feedback from supermassive black holes, dynamical interactions, or both?

JWST will address these questions, pushing to deeper limits and higher mapping speed than Hubble, but its physical resolution will be comparable to Hubble at their respective diffraction-limited wavelengths (Figure 4-1).

In the near-IR, JWST will see rest-frame visible light from galaxies at $z = 1-4$, not the star-forming regions and satellites shining brightly in UV light from young massive stars. These UV measurements will detect stars that have emerged from their birth environment, and so complement the mid-IR and Atacama Large Millimeter Array (ALMA).

Figure 4-3: A galaxy viewed by Hubble, JWST, and HDST at $z = 2$. The renderings show a one-hour observation (VIH for Hubble and HDST, $z_{JH}$ for JWST). Hubble and JWST detect the bulge and disk, but only the exquisite image quality of HDST resolves the galaxy's star-forming regions and its dwarf satellite. The zoom shows the inner disk region, where only HDST can resolve the star-forming regions and separate them from the redder, more distributed old stellar population. Image credit: G. Snyder (STScI).

1/3 galaxies at $z = 2 < 1$ kpc

important physics at sub-kpc scales

"From Cosmic Birth to Living Earths”

credit: Ceverino, Moody, & Snyder
Where are the mergers? Do they form 1st bulges?

galaxy mergers expected to be common at high-redshift, and form first compact galaxies

but dust-obscured, with faint tidal tails difficult to identify in deep HST images. 
-> need deeper, higher resolution images
star formation regulated by gas inflows/outflows/feedback
- stellar and supernova feedback (important at low mass)
- active galactic nuclei feedback (important at high mass)
- virial heating in massive halos

Illustris Simulation: dark matter → gas velocity

10 Mpc
Where are metals, gas outflows?

mass - metallicity relations on sub-kpc scales ⇒

constrain enrichment, metal-rich outflows, and pristine gas accretion (feedback, accretion, + mergers)
Super-Massive Black Holes/AGNs at $z > 1$?

bulge-formation correlated with SMBH-growth, AGN activity
AGN and shocks at z > 1 on 100 pc scales

Newman et al. 2014

HDST = 100 pc spatially-resolved rest-frame optical emission line tracers
- separate AGN-shocked regions from star-forming regions
& constrain importance of AGN-driven feedback at early-times
Summary

Detailed galaxy morphology can provide insight into the recent assembly history and test physical models of galaxy formation.

- *Galaxy evolution is complicated*;
  - need a richer set of morphological statistics to probe assembly processes

- Size-mass evolution at $0.5 < z < 3$. (lookback time $\sim 6$-$11$ Gyrs)
  -- central bulge formation proceeds shut-down of star-formation at $z > 1$
  -- smallest galaxies at a given mass form bulges, quench first
  -- highly disturbed galaxies are star-forming, large, more common at $z < 1$

**HDST:** $100$ pc scales everywhere!
- many high-redshift galaxies $< 1$ kpc
- where are the $z > 1$ mergers?
- separate and measure stellar, AGN feedback, gas flows at $\sim 100$ pc scales