GALAXY EVOLUTION

Evidence for mature bulges and an inside-out quenching phase 3 billion years after the Big Bang

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Most present-day galaxies with stellar masses \( \geq 10^10 M_\odot \) show no ongoing star formation and are dense spheroids. Ten billion years ago, similarly massive galaxies were typically forming stars at rates of hundreds solar masses per year. It is debated how star formation ceased, on which time scales, and how this “quenching” relates to the emergence of dense spheroids. We measured stellar mass and star-formation rate surface density distributions in star-forming galaxies at redshift 2.2 with ~1-kiloparsec resolution. We find that, in the most massive galaxies, star formation is quenched from the inside out, on time scales less than 1 billion years in the inner regions, up to a few billion years in the outer disks. These galaxies sustain high star-formation activity at large radii, while hosting fully grown and already quenched bulges in their cores. At the epoch when star-formation activity peaks in the universe (redshift \( z \approx 2 \)), massive galaxies typically lie on the so-called “star-forming main sequence.” Their star-formation rates (SFRs) tightly correlate with the mass in stars (stellar mass \( M_\ast \)), reaching up to several hundred solar masses (\( M_\odot \)) per year and producing a characteristic specific SFR (sSFR = SFR/\( M_\ast \)) that declines only weakly with mass (3, 4). In contrast, at the present epoch, such massive galaxies are spheroids with old stellar populations, which reach central surface stellar densities well above \( 10^9 M_\odot \) kpc\(^{-2} \) and host virtually no ongoing star formation. Although the most massive ellipticals at \( z = 0 \) bear the clear signatures of a gas-poor formation process (5, 6), the more typical population, at a mass scale of \( M \approx 10^9 M_\odot \), consists of fast rotators (7) with disk-like isophotes (8), steep nuclear light profiles (9), and steep metallicity gradients (10): all features that indicate a gas-rich formation process.

The full cessation of star-formation activity in these typical massive galaxies (here referred to as the quenching process) is not well understood, nor is its relation with the emergence of their spheroidal morphologies. Several quenching mechanisms have been proposed. The so-called halo-quenching scenario predicts that circumgalactic gas is shock-heated to high temperatures and

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SUPPLEMENTARY MATERIALS

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Supplementary Text
Figs. S1 to S4
Tables S1 to S3
Reference (19)
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stops cooling in dark matter halos above a critical mass \(\sim 10^{12} M_\odot\). Morphological/gravitational quenching proposes that the growth of a central mass concentration (i.e., a massive bulge) stabilizes a gas disk against fragmentation \((12, 13)\). Feedback from an accreting supermassive black hole transfers either radiative \((14)\) to the surrounding gas, thereby suppressing gas accretion onto the galaxy, or kinetic energy and momentum \((15)\), which causes the expulsion of gas from the galaxy.

Quenching must soon occur in the most massive, and thus far more readily star-forming, galaxies on the main sequence at \(z \sim 2\), to avoid dramatically overshooting the highest observed masses of \(z = 0\) galaxies \((16)\). Yet no general consensus has emerged on which of the above-mentioned processes is primarily responsible for halting this star formation as early as a few billion years after the Big Bang. Determining the distributions of the stellar mass and SFR densities within individual \(z \sim 2\) galaxies at high spatial resolution is central to resolving these issues. Together these distributions reveal how stellar mass builds up and SFR is progressively switched off inside these high-\(z\) galaxies, which, given their high masses, will have to evolve into “red and dead” systems by \(z = 0\).

We measured such quantities for a sample of 22 star-forming galaxies at a median \(z\) of 2.2 \((17\) and section S1). The sample spans a wide range in stellar mass \(M = 4 \times 10^{10}\) to \(5 \times 10^{11} M_\odot\) and SFR \(20\) to \(300 M_\odot\) year\(^{-1}\) and broadly traces the main sequence at these redshifts. The five most massive galaxies lie slightly below the average main sequence, a point we explore in more detail in section S1.

For all galaxies we obtained adaptive optics SINFONI (Spectrograph for INtegral Field Observations in the Near Infrared) spectroscopy on the European Southern Observatory’s Very Large Telescope, mapping the two-dimensional rest-frame H\(\alpha\) emission at \(\sim 1\) kpc spatial resolution. These data reflect the gas ionized by young stars within individual galaxies, which allows us to construct spatially resolved distributions of ionized gas kinematics and SFR surface densities internal to the galaxy. We also obtained Hubble Space Telescope (HST) imaging in the J and H passbands \((17, 18)\). At the redshifts of the sample, the J and H filters straddle the rest-frame Balmer/4000 Å break. This spectral feature is strong in relatively old stars and therefore provides a robust estimate of the stellar mass already assembled in older stellar populations. Thus, at a similar kiloparsec resolution as the SINFONI SFR maps, the HST images provide maps of the stellar mass density that is stored in such older underlying populations. Visual inspection of the two-dimensional SFR distributions immediately reveals their notoriously irregular appearance, with bright clumps at large radii, in contrast with their centrally peaked and smooth stellar mass distributions (figs. S4 to S6).

The shapes of the average surface SFR density \((\Sigma_{\text{sSFR}})\) profiles (Fig. 1, top panels) are very similar regardless of total mass and are well fitted by a Sérsic profile \(\Sigma \propto \exp(-b \times r^{1/b})\), with the \(n \sim 1\) value typical of disk-like systems. In contrast, the surface stellar mass density \((\Sigma_{\text{st}})\) profiles become progressively more centrally concentrated with increasing total stellar mass. The Sérsic index of the \(\Sigma_{\text{st}}\) profiles increases from \(n = 1.0 \pm 0.2\) in the low-mass bin, to \(n = 1.9 \pm 0.6\) in the intermediate-mass bin, up to \(n = 2.8 \pm 0.3\) in the high-mass bin (uncertainties indicate the 1σ scatter). Within each mass bin, the mean \(\Sigma_{\text{st}}\) profiles are always more centrally concentrated than the SFR density profiles.

We then compared the \(\Sigma_{\text{st}}\) profiles of our sample of \(z \sim 2.2\) galaxies with a mass-matched sample of local \(z = 0\) galaxies (Fig. 1, bottom panels) \((19)\). Consistent with the Sérsic fits, the low-mass \(z \sim 2.2\) galaxies have the same radial stellar mass profiles of late-type disks in the local universe. The \(z \sim 2.2\) galaxies in the most massive bin, however, have stellar mass profiles that overlap with those of \(z = 0\) early-type galaxies out to galactocentric distances of a few kiloparsecs, corresponding to typically \(\sim 2\) effective radii. At these high stellar masses \((\sim 10^{12} M_\odot)\), our sample of galaxies on the \(z \sim 2.2\) have therefore already saturated their central stellar mass densities to those of galaxies of similar mass at \(z = 0\), which are quenched systems with a bulge-dominated morphology. Thus the

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**Fig. 1. Stellar mass and star-formation rate surface density distributions.** The three panels of (a) to (c) show results for the three bins of stellar mass indicated at the top of each column, containing 9, 8, and 5 galaxies, respectively. (A) (upper row) The stellar surface mass density profiles (red, scale on the left vertical axis) and SFR surface density profiles (blue, scale on the right vertical axis) for our \(z \sim 2.2\) sample. Thin lines represent individual galaxies; the mean values are given by the solid circles (with error bars indicating the 1σ scatter). The derivations of these profiles are described in detail in the supplementary materials \((17)\). (B) (middle row) The mean sSFR as a function of radius \(r\) (sSFR; red line). In gray we show the 1σ scatter. (C) (bottom row) The average surface stellar mass density profiles of the star-forming \(z \sim 2.2\) galaxies (red points with dashed line; error bars indicate the 1σ scatter) overplotted on the average profiles for the mass-matched samples of \(z = 0\) galaxies (colors indicate morphological types: orange for early types, blue for late types).
bulge components of these massive galaxies are already fully in place while their hosts are still vigorously forming stars farther out in the surrounding (disk) regions (Figs. 1 and 2, center panels; see also (13)).

Specifically, the ratio between the star formation rate and stellar mass surface density profiles [i.e., sSFR = Σsfr(r)/Σstar(r)] indicates suppression of the inner sSFR, at the highest masses and generally outward-increasing radial profiles of sSFR, (Fig. 1, center panels). By examining the surface stellar mass density within 1 kpc, ΣM,J,kpc as a function of total stellar mass M, we see that the massive galaxies at z~2.2 in our sample have substantially suppressed star-formation activity in their centers relative to lower-mass galaxies at the same epochs. We show in the supplementary materials (17) that this cannot be entirely due to dust effects. The sSFR,1kpc _values range from sSFR,1kpc ~ 5 per billion years (Gy⁻¹) (corresponding to a mass-doubling time of ~200 My at a galaxy stellar mass of 10¹¹ M☉) down to negligible values of ~0.1 Gy⁻¹ at 10¹² M☉. The key conclusion is therefore that these galaxies sustain their high total SFRs at large radii, far from their central dense cores, whereas in such cores the sSFR, is about two orders of magnitude lower.

A further important consideration that emerges from the analysis of Fig. 2 is that our galaxies lie around the identical tight ΣM,J,kpc,M sequence that is traced by galaxies at z~0 (20). This implies that the increase in total M of individual galaxies along the main sequence must be accompanied by a synchronized increase in central ΣM,J,kpc until the maximal central stellar densities of today’s massive spheroids are reached at a stellar mass scale on the order of ~10¹¹ M☉. Below this galaxy mass scale, dense stellar bulges are therefore built concurrently with the outer galactic regions. At z=0, the global relation curves, because the quenched galaxies have a shallower slope than the star-forming galaxies, and a clear “ridge” emerges (Fig. 2) (21). We have too few galaxies to track this curvature at earlier times, but this trend would be consistent with z~2.2 galaxies slightly increasing their total M through declining star-formation at large radii while maintaining their already quenched inner ΣM,J,kpc values.

These results provide insight into the bulge formation process. The high stellar densities that are already present in their cores indicate that at least some massive star-forming galaxies at z~2.2 have today’s massive spheroids as their descendants. We are seeing, however, neither classical bulges formed by dissipationless merging nor pseudo-bulges formed by the slow secular evolution of a stellar disk. Such a dichotomy is often invoked to explain the structural variety observed in nearby galactic bulges ([22]; see, however, [23]). The high central stellar densities of the massive galaxies in our sample argue for a gas-rich, dissipative bulge formation process at even earlier epochs. This is consistent with theoretical predictions (24) that either mergers or violent disk instabilities in gas-rich galactic structures at high redshifts lead to a compaction phase of the gas component, which possibly even drags any preexisting stellar component within the inner few kiloparsecs.

Furthermore, the suppressed central sSFRs in such massive systems argue for a quenching engine also at work. As this apparently acts from the inner galactic regions outward, it echoes findings recently reported for massive galaxy populations in a more recent era, at z~0.5 to 1.5, or ~1.5 to 5.5 Gyr later (25, 26). Our results reveal that similar signatures can be seen as early as z~2.2, implying that the same physical processes that lead to a phase of suppressed star formation from the inside out started acting on massive star-forming galaxies as early as ~3 Gyr after the Big Bang. We also estimate the time scale for an

**Fig. 2. Central stellar mass density sequence.** We plot the stellar mass surface density within 1 kpc, ΣM,J,kpc as a function of the total stellar mass M. The black points show the z~0 ZENS sample, and the blue and red contours their density on the ΣM,J,kpc,M plane split for star-forming (blue) and quiescent (red) galaxies. The correspondingly colored solid lines indicate the best fits to these z~0 star-forming (ΣM,J,kpc = M¹/º) and quiescent (ΣM,J,kpc = M⁻¹/º) galaxies. The dashed black line shows the fit to the ridge of passive galaxies in the Sloan Digital Sky Survey z~0 sample of Fang et al. (20). The error bars at the bottom right indicate the systematic uncertainty in the derivation of ΣM,J,kpc and M. The large points are the z~2.2 galaxies, color coded according to specific star-formation rate within 1 kpc, sSFR,J,kpc. The z~2.2 galaxies lie on the tight ΣM,J,kpc,M locus traced by the z~0 population. In contrast with total SFRs increasing with stellar mass along the main sequence, the z~2.2 galaxies have central sSFRs that strongly decrease with stellar mass.

**Fig. 3. Outward progression of the quenching wave.** The quenching time t quench in star-forming ~10¹² M☉ galaxies at z~2.2 as a function of galactocentric distance. Such galaxies quench from inside out on time scales in the inner cores much shorter than 1 Gyr after observation, up to a few billion years in the galactic peripheries. The galaxies will be fully quenched by z~1. The solid orange line indicates the mean quenching time for all galaxies in the highest-mass bin, whereas the orange-shaded region marks the 1σ scatter.

**Fig. 4. Proposed sketch of the evolution of massive galaxies.** Our results suggest a picture in which the total stellar mass and bulge mass grow synchronously in z~2 main sequence galaxies, and quenching is concurrent with their total masses and central densities approaching the highest values observed in massive spheroids in today’s universe.
inside-out quenching wave to propagate across \( \sim 10^{21} M_{\odot} \) galactic bodies (Fig. 3). The estimate assumes that our galaxies keep forming stars with their observed radial profiles of surface SFR density until their \( \Sigma_{\text{SFR}} \) reaches the value observed in \( z = 0 \) passive galaxies of similar stellar mass. This allows quenching time scales substantially less than 1 Gyr in the galaxy centers and roughly 3 Gyr in the outer disk/ring regions. These give rise to a stellar age gradient of dlog(age)/dlog(r) \( \sim -0.5 \) dex per radial decade (17). This predicted age gradient in the stellar population implies a negative color gradient in passive \( z = 1 \) to 2 spheroids, which is found in several studies (27, 28); with flat metallicity gradients, the inferred average age gradients range between 

\[ \approx 0.1 \text{ and } 0.4 \text{ dex per radial decade.} \]

A contribution to the color gradient from either dust or metallicity effects would imply that such estimates are lower limits to such photometrically estimated stellar age. The galaxies will be fully passive on the timescale of the quenching rate, which may be less than 1 Gyr in the galaxy centers and possibly much longer in the outer regions (27, 28). This allows quenching time scales substantially less than 1 Gyr in the galaxy centers and roughly 3 Gyr in the outer disk/ring regions. This results in a quenching wave propagating across \( \sim 10^{21} M_{\odot} \) galactic bodies (Fig. 3). The estimate assumes that our galaxies keep forming stars with their observed radial profiles of surface SFR density until their \( \Sigma_{\text{SFR}} \) reaches the value observed in \( z = 0 \) passive galaxies of similar stellar mass. This allows quenching time scales substantially less than 1 Gyr in the galaxy centers and roughly 3 Gyr in the outer disk/ring regions. These give rise to a stellar age gradient of dlog(age)/dlog(r) \( \sim -0.5 \) dex per radial decade (17).

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