The quenching of star-formation in galaxies

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Galaxies: complexity in process and simplicity in outcomes

Physical processes in individual objects:
- Complexity

The evolving population:
- Simplicity
The Main Sequence: what do we mean by “quenching”? 

Brinchmann et al 2004

Quenches refer to what makes some galaxies lie in the "red cloud" rather than the Main Sequence, with sSFR << sSFR_{MS}
Main Sequence evolution from a gas regulator

\[ \Psi = (1 - r) \text{SFR} + \Phi + \frac{dm_{\text{gas}}}{dt} \]

Wind-loading
\[ \lambda = \frac{\Phi}{\text{SFR}} \]

SF efficiency
\[ \varepsilon = \frac{\text{SFR}}{m_{\text{gas}}} = \tau_{\text{dep}}^{-1} \]

\[ \left( \frac{m_{\text{gas}}}{m_{\text{star}}} \right) = s\text{SFR} \times \varepsilon^{-1} \]

Key feature of this system: if \( \lambda \) and \( \varepsilon \) are constant and if the system is fed at some specific accretion rate (sMIR) then the system produces \( s\text{SFR}=s\text{MIR} \), independent of the values of \( \lambda \) and \( \varepsilon \).
Control is reversed: \( \text{sMIR} - s\text{SFR} - \frac{m_{\text{gas}}}{m_{\text{star}}} \) via \( \varepsilon \).
Metallicity as a test of the gas-regulator

Lilly et al (2013)

\[ Z_{eq} = Z_0 + \frac{y_R}{1 + \lambda (1 - R)^{-1} + \epsilon^{-1} \cdot \left( sSFR + (1 - R)^{-1} \frac{dln\mu}{dt} \right)} \]

\[ = Z_0 + f_{\text{star}} \ y_R \]

- explains (s)SFR as second parameter in \( Z(m) \)
- \( Z(z) \) reflects the state of regulator system \( (\epsilon, \lambda, sSFR) \) not its history (because \( \tau_{\text{gas}} < \tau_H \))
- \( Z(m,SFR) \) which will change with \( z \) only if \( \epsilon \) or \( \lambda \) change (i.e. expect redshift-independent FMR)
- Three-way links: \( Z(m), m_{\text{star}}/m_{\text{halo}} \) and \( sSFR/sMIR \)

\( \tau_{\text{dep}} \sim 2.5 m_{10}^{-0.3} \) Gyr
\( \lambda \sim 0.3 \ m_{10}^{-0.8} \)

Fitting this surface:

- \( rsSFR \sim \frac{1}{1 - \eta} \) sMIR \( \sim 2 \) sMIR
- \( m_{\text{star}} \propto m_{\text{halo}}^{\frac{\lambda}{(1 - \eta)} - 1} \sim m_{\text{halo}}^{1.7} \)

\( Z \propto m_{\text{star}}^\eta \)

\( m_{\text{halo}} \sim 5 \)

:\( y_R \)

12 + log [O/H]
The “grow and quench” paradigm

Factor of 20 decline in sSFR since z = 2

Continuous “flow” of galaxies along the conveyer belt

1970’s cartoon by Bruno Bingelli?
Cosmological importance of quenching

Inefficient star formation (winds)

Inefficient SF due to winds

Quenching

Slowing down of structure growth leading to decline in sSFR_{MS}

\(\Omega_B/\Omega_{cdm}\) ceiling

"Quenching"

m_{star}/m_{halo} vs. m_{halo}

From Birrer et al 2014

Madau+Dickinson 2014

Half due to decrease of SF_{MS} and half due to quenching

\(\log(\langle M_{\odot} \text{year}^{-1} Mpc^{-3} \rangle) \times 10\)
Is quenching real? c.f. Pre-ordained evolution

RETURN TO [LOG-]NORMALCY: RETHINKING QUENCHING, THE STAR FORMATION MAIN SEQUENCE, AND PERHAPS MUCH, MUCH MORE

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\[ SFRD(t) = \frac{A_{Uni}}{\sqrt{2\pi r_{Uni}^2}} \exp \left[ -\frac{(\ln t - T_{0, Uni})^2}{2r_{Uni}^2} \right] \]

Abramson+ 2016, Gladders+2013

2000 galaxies
Pre-ordained or cosmological conveyor belt? Does it matter?

Yes! The questions you ask depends on what (picture) is in your head:

Conveyor belt “grow-and-quench”
• What drives the evolution of the Main Sequence?
• What quenches SF in galaxies and on what timescale?

“Pre-ordained”
• Why is there apparent “down-sizing”
• Why is the SFR history in individual galaxies apparently log-normal?

Also likely to give rather different perspectives on
• Gas content – driver or consequence?
• Chemical evolution – modified-closed-box or flow-through?
• Environment effects – imprinted at birth or accident later?
• Structure (spheroid vs. disk) – spheroids from short $\tau$ or at early epoch?
Quenching
Separability of $f_q(m_{\text{star}}, \rho)$

Baldry+ 2007, Peng+ 2010

"environment quenching" (= satellites)

$$f_{\text{blue}}(m, \rho) = \left(1 - \varepsilon_m(m)\right) \times \left(1 - \varepsilon_\rho(\rho)\right)$$

"mass quenching"

This terminology gives scope for confusion: which mass is relevant?
- Stellar mass?
- Black hole mass?
- Halo mass? But this is also "environment"!!
Mass-quenching

Only “mass quenching” depends on mass, and therefore it is that process that controls the shape of the mass function of the surviving star-forming galaxies, i.e. Schechter $M^*$.

$M^*$ is $\sim$ constant since $z \sim 4$

$$\eta = \frac{1}{M^*} \cdot SFR \iff P(m) = \exp\left(\frac{m}{M^*}\right)$$

Possible physical processes for “mass-quenching”:

- Halo effects linked to halo mass $m_{\text{halo}}$
- AGN feedback effects linked to black hole mass $m_{\text{BH}}$
- Internal effects linked to $m_{\text{star}}$ or structural effects such as surface density $\Sigma$, or B/T, or $\sigma_V$ etc

“Halo quenching”

“AGN-quenching”

“Morphological-” or “gravitational-quenching”
**Environment- (satellite-) quenching**

“Environment/satellite-quenching” is that process that quenches a galaxy because it is a satellite of another galaxy, described by

\[ \varepsilon_{\text{sat}} = \frac{1-f_{q,\text{sat}}}{1-f_{q,\text{cen}}} \]

\( \varepsilon_{\text{sat}} \) is strikingly independent of satellite galaxy mass.


Physical possibilities:

- Ram-pressure stripping of gas
- Tidal stripping
- Strangulation (starvation of gas inflow)
- Harrassment by neighbours
- + others…
How does $\varepsilon_{\text{sat}}$ vary with different parameters?

Why is $\varepsilon_{\text{sat}}$ independent of satellite mass?
How does $\epsilon_{\text{sat}}$ vary with different parameters?

Distribution of “drivers” (i.e. $m_{\text{halo}}$, $R$, and $\delta$) are largely independent of $m_{\text{sat}}$. But why is the “response” to these drivers evidently independent of satellite mass?
Timescales of environment/satellite quenching?

Several clues:

- $\epsilon_{\text{sat}}$ independent of $m_{\text{sat}}$?
- $\epsilon_{\text{sat}} \sim 0.5$, and increasing with $m_{\text{halo}}$
- small $\Delta sSFR$ between satellites and field ($\leq 0.08$ dex)

Estimates of $t_{\text{delay}} \sim 2\text{-}4$ Gyr (cf 1 Gyr $t_{\text{ff}}$)

See also Cibinel+2013, Carollo+2016
Trying to identify the relative importance of different physical quenching processes
The difficulties of establishing causality

**A cautionary example:**
Very strong observed correlations between quenched state (sSFR) of a galaxy and
- surface mass density $\Sigma$ (Kauffmann+ 2003), with $\Sigma_{\text{crit}}$ evolving as $(1+z)^2$ (Franx+ 2008).
- Sersic indices (Blanton+ 2003, Wuyts+ 2011).
- Bulge mass (Bluck+ 2015).

Structure could produce quenching directly, e.g. via disk stability (Martig+2009, Genzel+ 2014) or indirectly (e.g. via black hole mass following $m_{\text{bulge}}$ etc)

But we know $r_e(m)$ at fixed $m$ evolves roughly as $(1+z)^{-1}$. Are quenched galaxies dense because density quenched them, or simply because they stopped evolving at high $z$ when all galaxies were denser?
Appearance of strong $\Sigma$ threshold

Very strong correlation with $\Sigma_e$ (and difference between centrals and satellites) both reproduced by a toy-model in which $h_{\text{SF}}$ evolves as $m_{\text{star}}^{0.3} (1+z)^{-1}$ and quenching depends only on mass and not at all on structure!
Where $\Sigma_{\text{thresh}}$ comes from and why satellites are different than centrals

**Conclusion:** The strikingly strong correlation of quenched fraction and surface mass density $\Sigma_e$ is likely a coincidental result of quenching, not a driver of it. But what about spheroids?
Two (poorly understood) clues about quenching

- Galactic conformity
- The coincidence of quenching
1. Conformity

Satellite quenching is 2.5 times stronger with quenched centrals even when you match the satellites in all five of $M_{\text{halo}}$, $m_{\text{cen}}$, $m_{\text{sat}}$, $R$, $\delta$.

"Conformity" (Weinmann+ 2006)

(One-halo) conformity suggests that there is a very close connection between mass-quenching and environment-quenching via “halo-wide” effects.
2. The coincidence of quenching

Why does “quenching” happen just as \( m_{\text{star}} / m_{\text{halo}} \) approaches to within a factor of a few of the maximum efficiency (cosmic baryon fraction)? What is this telling us?
The explanation? a link between SN- and AGN-feedback?

Black holes are able to grow to “dangerous” levels only when SN-driven feedback becomes less efficient at expelling gas from the galaxy or halo.

1. Hydro simulations  (Seth: Dubois+2015, EAGLE: Bower+2017)
2. Semi-analytic models - see Henriques et al, 2017 (in prep.)

Is AGN feedback responsible for quenching?

Outflows of gas in AGN produced by “feedback” from active AGN: There is good evidence for major outflows of ionized and molecular gas (e.g. Cicone+2014, Fiore+2017) but:

• this is not the same as quenching (e.g. high mass-loading $\lambda$ in star-forming galaxies) and
• These outflows may well not affect gas in star-forming disk (e.g. Gabor+Bornaud 2014)

“Radio-mode” energy injection from quiescent BH into the hot gas in the CGM/ICM (e.g. Croton 2006)

• There is good evidence of interaction (bubbles etc).
• Main argument: can’t think of anything else energetic enough, so we put it in by hand (proportional to BH mass).
But is the “quenching mechanism question” well-posed?

What if there is a gate-keeper?

i.e. Process A keeps trying to quench the galaxy, but Process B doesn’t allow it until some other conditions are satisfied

Which of A or B is then actually “quenching”?
Back to the role of gas: major questions

What is the relative importance in quenching of
• fast removal of gas
• fast consumption of gas
• cessation of inflow followed by slow depletion ("starvation")
• suppression of star-formation efficiency

Prospective/promising diagnostics:
• Relative metallicities of stars in SF and quenched galaxies (see Peng+ 2015)
• Timescales of quenching (e.g. Wetzel 2013)
• (Molecular) gas content of quiescent galaxies
Points to take away

General points:
The outcome of complex galaxy evolution seems to have been remarkably simple. Focusing on these simple outcomes:
• constrains output of more physical models
• can provide new insights (e.g. reversed causality of regulator)
• can show what should not be causally inferred from observations

More specific points:
• The constant quenching mass of mass-quenching (stellar, also halo?) over a wide range of cosmic time.
• The separability of mass- and environment- quenching may well hide deep connections between the two, as shown by conformity and shows that quenching is a halo-wide phenomenon
• The “coincidence” of quenching links the failure of SN-feedback with quenching → BH driven quenching via the halo?
• Major task ahead: understanding role of gas in quenching (starvation, consumption, ejection, etc).