Galaxy Formation and Evolution in the Big Data Era

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You are most welcomed to visit us!
Galaxy Formation and Evolution Group @ KIAA-PKU
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Chengpeng Zhang
Gas, star formation, quenching, Gas regulation, chemo-evolution HI

Zhongyi Man
Galaxy surveys (spec/photo-z), large-scale structure, environmental effect, Galaxy properties on DM Halo

Petchara Pattarakijwanich, KIAA Fellow
Multi-wavelength Modeling of Stellar Population, Post-starburst Quasars and Their Role in Star-formation Quenching

Jing Dou
Gas, star formation, quenching, Gas regulation, chemo-evolution CO

Kexin Guo, KIAA Postdoc
star formation, quenching, Structure and morphology, IFU-MaNGA

Students/Postdocs/Collaborators/Visitors are most welcome!
the many aspects of the evolving galaxy population

- stellar mass: based on models of stellar population (easy) or dynamics (harder)
- star formation rate (SFR)
- gas content (HI and H₂)
- gas phase metallicities (abundance of heavy elements)
- stellar metallicity
- stellar age

Structure and morphology:
- sizes and densities
- Spheroid and disk (e.g. budge-to-disk)
- surface brightness profile (e.g. Sersic profile)

Environment:
- dark matter halo mass (from groups, lensing, abundance matching)
- Local projected surface density
distance to the Nth nearest neighbor
central galaxy or satellite?
distance to the BCG
Location in the cosmic web of filaments, clusters, sheets and voids.
Galaxy Evolution

Playing God of the Universe
Halo $\rightarrow$ Gas $\rightarrow$ Stars

“Reverse Engineering” of the Universe
Stars $\rightarrow$ Gas $\rightarrow$ Halo

Richard Bower:
“We haven’t understood galaxy formation, until we have translated the simulation results in a coupled set of differential equations (to be put in a SAM)”

Peng:
We haven’t understood galaxy formation, until we have translated the data in a coupled set of differential equations (to be put in a simulation)”
The Evolving Galaxy Population

The distribution function – continuity approach
\[ \phi(t, SFR, m_{\text{star}}, \rho, m_{\text{halo}}, \text{morphology}, \text{central/satellite, } Z, m_{\text{gas}} \ldots) \]

The scaling relation – gas regulation approach

What’s the key processes that regulate galaxy evolution?
What’s the physical interrelationship between different parameters?
A key issue in understanding the evolving galaxy population

**What we want to observe:**
continuous evolution of the galaxy population with time, like a movie.

**What we observed:**
galaxy population at different epoch, like a snapshot of a movie at different time

**progenitor problem:**
The $10^{11} \text{M}_{\odot}$ star-forming galaxy at $z \sim 2$ is very different from the $10^{11} \text{M}_{\odot}$ star-forming galaxy at $z \sim 0$

We need to reconstruct the evolutilonal sequence of the galaxy population as a function of time from observations at different epoch. → Continuity Approach
Large surveys enables new approach (SDSS, COSMOS, GOODS, VVDS, DEEP, GAMA etc.)

zCOSMOS + SDSS DR7  visualized by Yingjie Peng
key observational facts- The Star-forming Main Sequence

There are broadly two populations of galaxies on the basis of their specific star-formation rates ($sSFR=SFR/m_{\text{star}}$):
(cf. David Elbaz’s talk)

Blue star-forming galaxies
$(sSFR)^{-1} \sim \tau_H$

Red passive galaxies
$(sSFR)^{-1} >> \tau_H$

Renzini & Peng 2015
Two independent quenching processes
Peng et al. 2010

Central/Satellite Dichotomy
using Yang et al. group catalogue
van den Bosch et al. 2008, Peng et al. 2010

Reconstruct the evolitional sequence of the galaxy population via continuity equations

\[
\frac{\partial \phi(m, \rho, t)}{\partial t} + \left( \frac{\partial}{\partial \log m} \frac{\partial}{\partial \log \rho} \right) \hat{m} + \frac{\partial}{\partial \log \rho} \hat{\rho} \right) \phi(m, \rho, t) \left( \frac{\partial}{\partial t} \hat{m} + \frac{\partial}{\partial t} \hat{\rho} \right) = -\eta \phi(m, \rho, t)
\]

\[\phi_{\text{passive,cen}}(m, \rho, t) \quad \phi_{\text{passive,sat}}(m, \rho, t) \]
\[\phi_{\text{SF,cen}}(m, \rho, t) \quad \phi_{\text{SF,sat}}(m, \rho, t) \]
Galaxy Stellar Mass Functions

Schechter 1976

Ilbert et al. 2010

Star-forming

Ilbert et al. 2013

Star-forming

all galaxies (star-forming + passive)

Double-Schechter function

SDSS - Baldry et al. 2008
The required form of the mass quenching rate

\[
\frac{\partial N}{\partial t} + \nabla \cdot (N \nu) = \sigma
\]

**basic continuity equation**

at fixed mass and environment:

\[
\frac{\partial \phi_{\text{blue}}(t)}{\partial t} + \frac{\partial}{\partial \log m} \left[ \phi_{\text{blue}}(t) \frac{\partial \log m}{\partial t} \right] = -[\lambda_m(t) + \kappa_\text{e}(t)]\phi_{\text{blue}}(t)
\]

\[
\frac{1}{\phi_{\text{blue}}(t)} \frac{\partial}{\partial \log m} \left[ \phi_{\text{blue}}(t) \frac{\partial \log m}{\partial t} \right] = sSFR(t)\beta
\]

\[
\alpha = \frac{\partial \log \phi_{\text{blue}}(t)}{\partial \log m} = (1 + \alpha_s) - \frac{m}{M^*}
\]

\[
\beta = \frac{\partial \log sSFR(t)}{\partial \log m}
\]

\[
\frac{1}{\phi_{\text{blue}}(t)} \frac{\partial \phi_{\text{blue}}(t)}{\partial t} = -sSFR(t)\alpha - \lambda_m(t) - \kappa_\text{e}(t)
\]

\[
= -sSFR(t)(1 + \alpha_s + \beta) + \frac{SFR(t)}{M^*} - \lambda_m(t) - \kappa_\text{e}(t)
\]

\[
\lambda_m(t) = \frac{SFR(t)}{M^*} + C(t)
\]

low mass galaxies in low density environments are still all blue

\[
\lambda_m(t) = \frac{SFR(t)}{M^*}
\]
The required form of the mass quenching rate

**Continuity Equation**

Mass-Quenching Rate:
\[ \dot{\lambda}_m(t) = \frac{SFR(t)}{M^*} \]

**Observations**

**Survival probability:**
\[ P = \exp \left( - \frac{m}{M^*} \right) \]

Quenching occurs, statistically, when a galaxy has formed \( M^* \) of stars.
Baldry et al. 2012:
“This supports the empirical picture, quenching model, for the origin of the Schechter function by Peng et al. (2010)”
Star-formation and Quenching

In this simple picture, all star-forming galaxies have similar specific star-formation history. What makes the differences are the different quenching epoch and different quenching channel.

Downsizing is produced by quenching.
The Evolving Galaxy Population

The distribution function – continuity approach
\( \phi(t, SFR, m_{\text{star}}, \rho, m_{\text{halo}}, \text{morphology}, \text{central/satellite}, Z, m_{\text{gas}} \ldots ) \)

The scaling relation – gas regulation model

What’s the key processes that regulate galaxy evolution?
What’s the physical interrelationship between different parameters?
Gas regulation in galaxies


\[ SFR = \varepsilon M_{gas} \]

\[ \Psi = \lambda \cdot SFR \]

The change of mass in...

**stars**

\[ \frac{dM_{star}}{dt} = (1 - R)SFR \]

**gas**

\[ \frac{dM_{gas}}{dt} = \Phi - (1 - R)SFR - \Psi \]

**metals**

\[ \frac{dM_{Z, gas}}{dt} = y \cdot SFR - Z(1 - R)SFR - Z\Psi + Z_0 \cdot \Phi \]
The dynamics of the gas regulator model (Peng & Maiolino 2014)

gas inflow rate of the galaxy $\Phi$, star-formation efficiency $\varepsilon$, mass-loading factor $\lambda$
equilibrium timescale $\tau_{eq} = \frac{1}{\varepsilon (1 - R + \lambda)} = \frac{1}{sSFR \cdot (1 - R + \lambda)} \frac{f_{gas}}{1 - f_{gas}}$

**General Solution**

<table>
<thead>
<tr>
<th>$M_{gas}(t)$</th>
<th>$\Phi \tau_{eq}(1 - e^{-\frac{t}{\tau_{eq}}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SFR(t)$</td>
<td>$\Phi \tau_{eq} \varepsilon (1 - e^{-\frac{t}{\tau_{eq}}})$</td>
</tr>
<tr>
<td>$M_{star,int}(t)$</td>
<td>$\Phi \tau_{eq} \varepsilon [t - \tau_{eq} (1 - e^{-\frac{t}{\tau_{eq}}})]$</td>
</tr>
<tr>
<td>$M_{star}(t)$</td>
<td>$(1 - R) \times M_{star,int}(t)$</td>
</tr>
<tr>
<td>$sSFR_{int}(t)$</td>
<td>$\frac{1 - e^{-\frac{t}{\tau_{eq}}}}{t - \tau_{eq} (1 - e^{-\frac{t}{\tau_{eq}}})}$</td>
</tr>
<tr>
<td>$sSFR(t)$</td>
<td>$sSFR_{int}(t) / (1 - R)$</td>
</tr>
<tr>
<td>$f_{gas}(t)$</td>
<td>$\frac{1}{1 + \varepsilon (1 - R) \left( \frac{t}{\tau_{eq} - \frac{t}{\tau_{eq}}} \right)}$</td>
</tr>
<tr>
<td>$\Psi(t)$</td>
<td>$\Phi \tau_{eq} \lambda (1 - e^{-\frac{t}{\tau_{eq}}}) = \Phi \frac{\lambda}{1 - R + \lambda} (1 - e^{-\frac{t}{\tau_{eq}}})$</td>
</tr>
<tr>
<td>$Z_{gas}(t)$</td>
<td>$[Z_0 + y \tau_{eq} \varepsilon (1 - e^{-\frac{t}{\tau_{eq}}}) \left[ 1 - e^{-\frac{t}{\tau_{eq} \left( 1 - e^{-\frac{t}{\tau_{eq}}} \right) \right}]}$</td>
</tr>
<tr>
<td>$Z_{star}(t)$</td>
<td>$Z_{gas} [1 - e^{-sSFR \cdot (1 - R) t}]$</td>
</tr>
</tbody>
</table>

**Equilibrium Solution ($t \gg \tau_{eq}$)**

| $M_{gas} \Phi \tau_{eq}$ | $\Phi \tau_{eq} \varepsilon = \frac{\Phi}{1 - R + \lambda}$ |
| $SFR(t)$ | $\Phi \tau_{eq} \varepsilon (1 - \tau_{eq}) \sim \Phi \tau_{eq} \varepsilon t$ |
| $M_{star,int}(t)$ | $(1 - R) \times M_{star,int,eq}(t)$ |
| $sSFR_{int,eq}(t)$ | $\frac{1}{t - \tau_{eq}} \sim \frac{1}{t}$ |
| $sSFR(t)$ | $sSFR_{int,eq}(t) / (1 - R)$ |
| $f_{gas}(t)$ | $\frac{1}{1 + \varepsilon (1 - R) \left( t - \tau_{eq} \right)} \sim \frac{1}{1 + \varepsilon (1 - R) t}$ |
| $\Psi(t)$ | $\Phi \tau_{eq} \lambda = \Phi \frac{\lambda}{1 - R + \lambda}$ |
| $Z_{gas}(t)$ | $Z_0 + y \tau_{eq} \varepsilon = Z_0 + \frac{y}{1 - R + \lambda}$ |
| $Z_{star}(t)$ | $Z_{gas} \left( 2 \right)$ |
Quenching/Star Formation Suppression

Morphological Transformation

Silk & Mamon 2012

Cattaneo 2016
**Quenching**

**Mass-quenching (internal-quenching):**
- Strongly mass-dependent
- independent of local density
- $M^*$ independent of epoch (to $z > 4$)
- applies equally to all galaxies centrals and satellites

*Obvious possibilities:*
- Limit to halo mass sustaining star-formation
- AGN feedback
- SF feedback
- Other processes linked to mass of galaxy....

*Main difficulty:*
For centrals $M_{\text{star}} M_{\text{BH}}$ & $M_{\text{halo}}$ tightly correlated

**Environment-quenching (external-quenching):**
- independent of stellar mass
- dependent on local density and/or halo-centric radius
- Independent of halo mass at same density
- only for satellites
- might not associate with morphological transformation

*Obvious possibilities:*
- Strangulation
- Ram pressure stripping
- Tidal effects
- Harassment
- Mergers

*Observationally, the primary mechanism responsible for star formation quenching in galaxy population is still unclear.*
stellar metallicity is a powerful tool to discriminate between different scenarios

Quenching by sudden gas removal

- gas accretion
- gas removal
- accreting star forming galaxy
- star formation stops
- passive galaxy

Quenching by strangulation

- gas accretion
- no more inflow (strangulation)
- accreting star forming galaxy
- star formation continues with available gas
- passive galaxy
The significant $\Delta Z_{\text{star}}$ in SDSS strongly support that local quiescent galaxies with $M_{\text{star}} < 10^{11} M_{\odot}$ are primarily quenched as a consequence of “strangulation” (i.e. cut off the gas inflow).

Massive galaxies with $M_{\text{star}} < 10^{11} M_{\odot}$ can be explained by both strangulation and fast gas removal.
stellar metallicity enhancement in a “close-box” model

The observed mass-dependent $\Delta Z_{\text{star}}$ is consistent with the strangulation scenario in which quiescent galaxies at $M<10^{11} \, M_{\odot}$ are on average observed 4 Gyr after quenching due to strangulation, largely independent of stellar mass.
Stellar ages for star-forming and quiescent galaxies
Stellar ages for star-forming and quiescent galaxies

Peng, Maiolino & Cochrane 2015, Nature

The age for all galaxies strongly depends on the stellar mass →
the red fraction strongly depends on stellar mass.

The dependence on stellar mass becomes much weaker once the whole sample is split into star-forming and quiescent galaxies.

the age difference is largely independent of mass, \( \sim 4 \text{ Gyr} \)

Remarkably consistent with the mass-independent time \( \Delta t \) from strangulation required to explain the difference of stellar metallicities.
our results are mainly based on metallicity differences and age differences between star-forming and passive galaxies ➢ uncertainties are much less critical

➢ strongly support that local quiescent galaxies with $M_{\text{star}} < 10^{11} M_{\odot}$ (i.e. the vast majority of galaxies) are primarily quenched as a consequence of “strangulation”.  

➢ gas removal by outflows (at low redshifts) plays a minor role in quenching galaxies  

➢ cannot shed light on the quenching mechanism at $M_{\text{star}} \geq 10^{11} M_{\odot}$  

→ need to perform the same analysis at high redshifts. M0ONS/JWST
"Reverse Engineering" of the Universe

Key Observational Facts from Large Surveys

\[ \phi_{cen,blue}(m, \rho, t) \xrightarrow{\text{mass-quenching}} \phi_{cen,red}(m, \rho, t) \]

\[ \phi_{sat,blue}(m, \rho, t) \xrightarrow{\text{mass-quenching}} \phi_{sat,red}(m, \rho, t) \]

translate complex data into several simple equations

translate complex data into several simple equations

translate complex data into several simple equations

Gas

gas-regulator model link Galaxies to Halos

mass conservation scaling relations

Cosmological Context \( \phi_{\text{halo}}(m_h, \rho, t) \)
continuity approach + gas regulation

SDSS Centrals

Model - Peng et al. 2017 in prep. Centrals

a

b

gas fraction

log stellar mass

log SFR

stellar mass

Peng+14 model z=0.05

Boselli+14 $X_{\text{CO}}=$ constant

Boselli+14 $X_{\text{CO}}=$ lum. dependent

log (Gyr$^{-1}$)
On-going and future projects

SDSS/GAMA

MOONS/PFS

VLT – VIMOS /SINFONI /KMOS

MaNGA

IRAM APEX JCMT

ALMA

Areco

FAST

SKA
MOONS-(Multi-Object Optical and Near-infrared Spectrograph for VLT)
System Overview

Optical to near-IR light (0.6µm-1.8µm simultaneously) dispersed in cryogenic spectrographs

Simultaneously 3 bands:
0.8-0.95µm at R = 8,000
1.17-1.26µm at R = 20,000
1.52-1.63µm at R = 20,000

Property of MOONS team
MOONS - Multi-Object Optical and Near-infrared Spectrograph for VLT

a SDSS-like machine probing the peak of galaxy and black hole formation

Integration 2-16hrs on source
400 nights
~1 Million galaxies at z > 1

Property of MOONS team