Evolution of the stellar mass function of galaxies to z~3 in MOIRCS Deep Survey

Masaru Kajisawa (Tohoku University)
This talk

- **MOIRCS Deep Survey (MODS)**
  Deep NIR imaging survey with Subaru and MOIRCS in the GOODS-North region.
  - Search for $z>7$ galaxies
  - **Evolution of stellar mass function**
  - Evolution of clustering properties
  - Star formation/AGN and stellar mass

- **Evolution of stellar mass function**
  - Evolution of integrated stellar mass density
    - when stars formed
  - **Evolution of stellar mass function**
    - How stellar mass assembly of galaxies proceeded in different mass ranges.

We used MOIRCS Deep Survey data to investigate the evolution of the stellar mass function over the wide range of mass back to $z\sim3$. 

Stellar mass function of galaxies at $z<0.05$
**$z=1\sim3$: Important era**

- Peak of star formation/AGN activities
- Active star formation in massive galaxies
- Strong evolution of stellar mass density
- Formation of Hubble sequence

Very important epoch in the histories of star formation and mass assembly of galaxies

How galaxies formed and evolved?
Importance of NIR data

✓ $z \sim 1-2$

Rest-NIR luminosity  →  Stellar Mass

✓ $z \sim 2-4$

Balmer/4000 Å break  →  Stellar age

M/L ratio

History of  Star formation

Mass assembly
MOIRCS

4 x 7 arcmin$^2$

Multi-Object InfraRed Camera and Spectrograph

Near-infrared (0.9~2.5 $\mu$m)

- large telescope
- wide F.O.V.
- high image quality

We can construct large NIR-selected sample to faint (low-mass) limit
MOIRCS Deep Survey (MODS) in GOODS-North Region

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GOODS-North
JHKs-bands deep imaging
MODS data (S06A~S08A)

4 pointings of MOIRCS cover 70% of GOODS-N

✓ GT-1, 3, 4 (wide, ~103 arcmin² including GT2)

<table>
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<th>J</th>
<th>H</th>
<th>K</th>
<th>Exposure (hr)</th>
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✓ GT-2 (deep, ~28 arcmin²)

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Comparison with other NIR surveys

**J-band**

- Forster-Schreiber et al. 2006
  - Very deep --- detect low-mass ($10^9$-$10^{10} M_\odot$) galaxies even at $z \sim 2-3$
  - Wide area --- measure the number density evolution with high accuracy

**K-band**

- Very deep --- detect low-mass ($10^9$-$10^{10} M_\odot$) galaxies even at $z \sim 2-3$
  - Wide area --- measure the number density evolution with high accuracy

Forster-Schreiber et al. 2006
Source detection in the K-band image
Multi-band photometry
  - \( U(KPNO), BViz(HST), JHK(MOIRCS), 3.6,4.5,5.8 \mu m(\text{Spitzer}) \)
Redshift determination (spec-z, photo-z)
  - distance \( \rightarrow \) luminosity, rest-frame SED
Multi broad-band SED fitting
  - fitting multi-band photometry with SED models \( \rightarrow \) stellar M/L ratio
  - \( L \) and M/L \( \rightarrow \) stellar mass
Estimate stellar mass function in each redshift bin
  - Vmax method
  - Sandage Tammann & Yahil method (maximum likelihood)
Sample

- **Wide** (103arcmin$^2$)
  
  6381 objects with $K_{\text{Vega}}<23\text{mag}$

- **Deep** (28arcmin$^2$)
  
  3161 objects with $K_{\text{Vega}}<24\text{mag}$

  total 7563 objects (with 2098 spectroscopic redshifts)

We investigated the evolution of stellar mass function over $0.5<z<3.5$.

<table>
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<th>Number of objects (spec-z)</th>
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<tr>
<td>0.5$&lt;z&lt;1.0$</td>
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<tr>
<td><strong>Wide</strong></td>
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<td><strong>Deep</strong></td>
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</table>
Photometric redshift

- **model template**
  - GALAXEV
  - PEGASE2
  - Maraston 2005

Different SED models

Check for systematic effects on

- Photo-z
- M/L ratio

✓ **EAZY** (Brammer et al. 2008)
  - Public photo-z code
  - Independent check for photo-z

EAZY uses templates based on the principal components

Estimate of M/L ratio

- GALAXEV
- PEGASE2
- Maraston
stellar mass limit

K-band magnitude limited sample

rest-frame U-V color distribution at each redshift
M/L ratio distribution as a function of mass

Stellar mass limit as a function of redshift

90% of objects with the limiting mass are detected at K<23 (24 for deep)
results
Number density of galaxies decreases with redshift.

Strong evolution at $\sim M^*$ ($\sim 10^{11} M_\odot$)

Low-mass end slope becomes steeper with redshift.
Results with different SED templates

- Different SED models
  - similar evolutionary trends

- Maraston model
  - smaller number density at high mass and high-z
Evolution of Schechter parameters

- **Normalization**
  - gradually decreases with redshift
  - ~10% of the local value at $z \sim 2$
  - and ~4% at $z \sim 3$

- **Characteristic mass**
  - No significant evolution
  - decreases at $z > 2$ in the case with Maraston model

- **Low-mass end slope**
  - becomes steeper with redshift
  - Some variance between the different SED models
Significant steepening of $\alpha$ is seen.
Check for the effect of photo-z uncertainty

We performed simulations for the effect of the photometric redshift error on SMF in high-z bins, assuming no evolution of the shape of SMF ($\alpha$ and $M^*$ are fixed to those in $0.5<z<1.0$ bin).

Although photometric uncertainty tends to make $\alpha$ steeper at high-redshift, the observed evolution of $\alpha$ is much stronger.
discussion
Average stellar mass density integrated down to $10^8 M_\odot$ decreases with redshift. The strength of evolution is consistent with those in other general fields.
Comparison with other studies

- $M^* \sim 10 \times M^* \left(10^{11-12} M_\odot\right)$
  - consistent with other studies

- low-mass end ($10^9-10^{10} M_\odot$)
  - slightly higher at high-z
  - systematic uncertainty in the mass estimation
  - incompleteness or fixing $\alpha$ in other shallower surveys
Mass-dependent number density evolution

- Number density decreases with redshift
- \( \sim M^* \) galaxies show stronger evolution than low-mass (0.01~0.1M*) galaxies
Contribution to stellar mass density in different mass ranges

- Stellar mass density also decreases with redshift
- The contribution of low-mass galaxies increases with redshift
Specific star formation rate of low-mass galaxies

SFR/Ms of low-mass galaxies tends to be higher even at high redshift.

Low-mass galaxies are expected to have higher growth rate of stellar mass by star formation activities.
Evolution of low-mass end slope

- SSFR distribution
  Mass growth rate of low-mass galaxies by star formation is higher than $\sim M^*$ galaxies
  Low-mass slope is expected to become steeper with time.

- $\alpha$ becomes shallower with time.
  Hierarchical merging $\rightarrow$ Mass function becomes flatter with time
  Hierarchical merging flatten with time $\leftrightarrow$ Star formation steepen with time
  Evolution of low-mass slope
  Hierarchical merging process played an important role for the stellar mass assembly of low-mass galaxies at high redshift.

Relative change of number density expected from SFR

Drory & Alvarz 2008
Comparison with semi-analytic model

- Low-mass end slope
  - similar evolutionary trend
  - steeper SMF at high-z
- Normalization
- Detailed shape
  - significantly different from the models

Bower et al. 2006

- Normalized with the uncertainty of stellar mass
- Convolved with the EXP kernel
Summary

- We used MODS data to investigate the evolution of the stellar mass function of galaxies down to \(10^{9-10}\,M_\odot\) over \(0.5<z<3.5\).

- Normalization of SMF and the integrated stellar mass density decrease with redshift. (~15% of the present value at \(z\sim2\), ~7% at \(z\sim3\))

- Evolution of number density of low-mass galaxies (\(0.01\sim0.1M^*\)) is weaker than that of \(~M^*\) galaxies. Low-mass end slope becomes steeper with redshift.

- Evolution of low-mass end slope suggests that the hierarchical merging process was important for the stellar mass assembly of low-mass galaxies.
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