Fraction of Clumpy Star-forming Galaxies in CANDELS/GOODS-S

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Clumps: Important Feature of Galaxies

- Seen in deep rest-frame UV (e.g., Elmegreen+07, 09, Guo+12), rest-frame optical images (e.g., Forster Schreiber+11, Guo+12), and emission line maps (e.g., Genzel+08, 11)

- Span a wide redshift range: 0.5<z<5

- Typical stellar mass: $10^7 \sim 10^9$ $\text{M}_\odot$, typical size: ~1 kpc

- Regions with blue UV—optical color and enhanced specific SFR (e.g., Guo+12, Wuyts+12)

- Have underlying disks, based on either morphological (e.g., Elmegreen+07,09) and kinematic (e.g., Genzel+11) analysis

Elmegreen et al. (2007)
Clumps: Ideal Laboratory of Star Formation, Feedback, and Structure Formation

- **Formation**: gravitational instability in the gas-rich turbulent disks (VDI)

Rotation!

Gravitational instability (Q<1)!

Turbulence!

Genzel et al. (2011)
Clumps: Ideal Laboratories of Star Formation, Feedback, and Structure Formation

Fate:

- In-ward migration towards the center to coalesce into bulges
- Quick disruption by tidal force or feedback

Guo et al. (2012)

Wuyts et al. (2012)
One Key Question Still Remains Unclear:

\[ F_{\text{clumpy}} (M^*, z) = \frac{\text{Number of Clumpy Galaxies with } (M^*, z)}{\text{Number of Galaxies with } (M^*, z)} \]

Probability of galaxies undergoing VDI, linked with the macro-physics of star formation

This work

Measuring \( F_{\text{clumpy}} \) of star-forming galaxies in CANDELS/GOODS-S

Sample

1. \( 0 < z < 3.5 \)
2. \( \log(M^*) > 9 \)
3. \( \text{SSFR} > 0.1/\text{Gyr} \)
**Identifying Clumpy Galaxies: I. Visual Classification**

- Visual classification done by CANDELS astronomers
- Each galaxy inspected by 3—5 different people
- 3X3 grid of (major clumps, blue patches) in V and H bands
- Diagonalized, normalized, and averaged:
  - 0.00 - no clumpy/no patches
  - 0.25 - 1-2 clumps/no patches OR no clumps/some patches
  - 0.50 - 3+ clumps/no patches OR 1-2 clumps/some patches OR no clumps/Lots of patches
  - 0.75 - 3+ clumps/some patches OR 1-2 clumps/lots of patches
  - 1.00 - 3+ clumps/lots of patches
- Limited only to H<24 AB galaxies
- Cannot tell clump positions
Identifying Clumpy Galaxies: II. Clump Finder

- Combining both: visual classification primary, clump finder secondary
General results:

I. $F_{\text{clumpy}}$ between 20% and 60% for different ($M^*$, $z$) bins

II. $F_{\text{clumpy}}$ vs. redshift differs for different mass bins

III. $F_{\text{clumpy}}$ peaks at $\log(M^*)=10-10.5$ for all redshift bins
Low-mass End:

- $F_{\text{clumpy}}$ increases toward low $z$
- Violent disk instability occurs later in low-mass galaxies
- Observational bias (cosmological dimming) flattens but does not eliminate the trend
Intermediate:

- $F_{\text{clumpy}}$ changes mildly along redshift.
- Clump formation is most efficient in this $M^*$ bin: the highest $F_{\text{clumpy}}$ among all redshift bins.
Massive End:

- $f_{\text{clumpy}}$ peaks during $z=1.0-1.5$

- Low-z end: disk stabilized (Dekel+09, Cacciato+12, Forbes+13), gas accretion rate dropped (Dekel+09), and low gas fraction (Geach+11)

- High-z end: disk stabilized by bulge or collapsed to nugget?
**Fraction of Clumpy Galaxies**

**Fclumpy vs. M***:

- Fclumpy peaks at \( \log(M^*) = 10 - 10.5 \) for all redshift bins.
- Observational biases (if any) mainly change the amplitude not the trend.
Both fractions drop at the massive ends with same trend at $z \sim 1$

Galaxies need to be gas-rich to form clumps

At the low-mass end, clumpy fraction drops more quickly than gas fraction: need mechanisms (e.g. radiative feedback) to prevent clump formation or destroy clumps
**Fraction of Clumpy Galaxies vs. SFE**

- **SFE = SFR / Baryon Accretion Rate (Behroozi+12, 13)**
- Good correlation at the low-mass ends
- Deviation at the most massive ends: something (AGN?) affecting SFE dose not affect Fclumpy
- Or quiescent galaxies dominate the most massive ends
Comparison with Simulation

- Zoom-in hydro cosmological simulations of 29 galaxies (Ceverino & Klypin 09, Ceverino+11, Deke+13)

- Clumps identified from 3-D gas snapshots (Mandelker+13)

- Only clumps with $\frac{M_{\text{clump}}}{M_{\text{disk}}}>0.01$ (both in-situ and ex-situ) counted

- Good agreement between observation and simulation
Summary

- A key question: the fraction of clumpy galaxies with \((M^*, z)\)
- Visual classification + clump finder on star-forming galaxies in CANDELS/GOODS-S
- \(F_{\text{clumpy}}\) between 20% and 60% for different \((M^*, z)\) bins
- \(F_{\text{clumpy}}\) vs. redshift differs for different mass bins
- \(F_{\text{clumpy}}\) peaks at \(\log(M^*)=10-10.5\) for all redshift bins
- \(F_{\text{clumpy}}\) vs. \(M^*\) shows the same trend of gas fraction for massive galaxies at \(z \sim 1\)
- Correlation between \(F_{\text{clumpy}}\) and SFE for low-mass galaxies
- Comparison with simulation: still on-going, but good preliminary agreement