arXiv:2305.09021

Fraction of Clumpy Star-Forming Galaxies at $0.5 \le z \le 3$ in UVCANDELS: Dependence on Stellar Mass and Environment

Zahra Sattari,[1,2] Bahram Mobasher,[1] Nima Chartab,[2] Daniel D. Kelson,[2] Harry I. Teplitz,[3] Marc Rafelski,[4,5] Norman A. Grogin,[4] Anton M. Koekemoer,[4] Xin Wang,[6,7] Rogier A. Windhorst,[8] Anahita Alavi,[3] Laura Prichard,[4] Ben Sunnquist,[4] Jonathan P. Gardner,[9] Eric Gawiser,[10] Nimish P. Hathi,[4] Matthew J. Hayes,[11] Zhiyuan Ji,[12] Vihang Mehta,[3] Brant E. Robertson,[13] Claudia Scarlata,[14] L. Y. Aaron Yung,[9] Christopher J. Conselice,[15] Y. Sophia Dai,[16] Yicheng Guo,[17] Ray A. Lucas,[4] Alec Martin,[17] and Swara Ravindranath[4]

ABSTRACT

High-resolution imaging of galaxies in rest-frame UV has revealed the existence of giant star-forming clumps prevalent in high redshift galaxies. Studying these sub-structures provides important information about their formation and evolution and informs theoretical galaxy evolution models. We present a new method to identify clumps in galaxies' high-resolution rest-frame UV images. Using imaging data from CANDELS and UVCANDELS, we identify star-forming clumps in an HST/F160W$\le$ 25 AB mag sample of 6767 galaxies at $0.5 \le z \le 3$ in four fields, GOODS-N, GOODS-S, EGS, and COSMOS. We use a low-pass band filter in Fourier space to reconstruct the background image of a galaxy and detect small-scale features (clumps) on the background-subtracted image. Clumpy galaxies are defined as those having at least one off-center clump that contributes a minimum of 10% of the galaxy's total rest-frame UV flux. We measure the fraction of clumpy galaxies (f_{clumpy}) as a function of stellar mass, redshift, and galaxy environment. Our results indicate that f_{clumpy} increases with redshift, reaching $\sim 65\%$ at $z \sim 1.5$. We also find that f_{clumpy} in low-mass galaxies ($9.5 \le \log(M_*/M_\odot) \le 10$) is 10% higher compared to that of their high-mass counterparts ($\log(M_*/M_\odot) > 10.5$). Moreover, we find no evidence of significant environmental dependence of f_{clumpy} for galaxies at the redshift range of this study. Our results suggest that the fragmentation of gas clouds under violent disk instability remains the primary driving mechanism for clump formation, and incidents common in dense environments, such as mergers, are not the dominant processes.

Clumpy銀河の赤方偏移進化・環境の影響

- Clumpy銀河
  - 遠方の星形成銀河で多く見られ、SFRが局所的に大きいことが特徴。
  - その起源は、銀河のdisk不安定性 (内的要因) やgas-rich merger (外的要因) が考えられるが、未だ明らかではない。
    - Clump合体によるbulge形成や、clump破壊によるthick disk形成という話も。
  - CANDELS/UVCANDELSのz~0.5–3 星形成銀河サンプル6767個から、rest 1600Aの画像 (をF160WのPSFに合わせてなましたもの) でclump構造を同定し、母銀河の性質との関係を調べる。

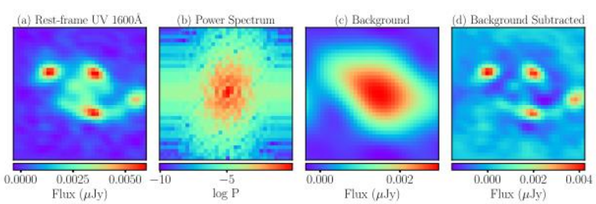

Figure 2. Two examples demonstrating the process of subtracting background from rest-frame UV images of galaxies. Panel (a) shows the galaxy image in the rest-frame UV filter. We calculate the power spectrum of this image in the Fourier space. Panel (b) shows log(power spectrum) in the frequency domain. After constructing the background map of the clump (Panel (c)), we remove it from the original image and the residual is an image which is ready to identify its clumps (Panel (d)).

Fig2: FFTによるclump同定→
rest-1600A画像をFFTし、低周波（＝実空間で広がった）成分を除去した画像上で3σ・4pixel以上の塊をclumpと同定。さらに、フラックスが全体の10%以上のものに限定 (50% completeness)。但し、bulge中心付近は除いた。

bulgeそのものやother bright sourceからのコンタミ(？)を除くため。

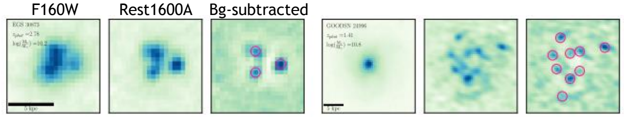

Figure 3. Eight examples of clumpy galaxies after identifying their clumps with magenta circles on their background-subtracted images in the right panels. Also, the left and middle panels show F160W and rest-frame UV 1600 Å images of these galaxies, respectively. In Section 3.2, we eliminate clumps that account for less than 10% of the total rest-frame UV flux of their host galaxies, resulting in a complete sample of clumpy galaxies. However, in this figure, we do not apply this requirement.

Fig3: clump同定例→

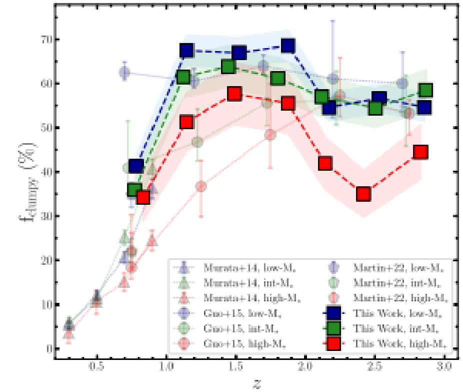

Figure 6. Fraction of clumpy galaxies as a function of redshift in three stellar mass bins (squares). Clumpy galaxies are those that have at least one off-center clump in their rest-frame UV images. Shaded regions correspond to 1σ uncertainty estimated from Poisson statistics. For comparison, measurements from Murata et al. (2014) (triangles), Guo et al. (2015) (circles) and Martin et al. (in preparation) (pentagons) are also added. The stellar mass bins in this works are the same as those of Murata et al. (2014) and Martin et al. (in preparation) (low-M$_*$: $9.5 \le \log(\frac{M_*}{M_\odot}) < 10$, int-M$_*$: $10 \le \log(\frac{M_*}{M_\odot}) < 10.5$, and high-M$_*$: $\log(\frac{M_*}{M_\odot}) \ge 10.5$). But Guo et al. (2015) binned the stellar mass of galaxies slightly different (low-M$_*$: $9 \le \log(\frac{M_*}{M_\odot}) < 9.8$, int-M$_*$: $9.8 \le \log(\frac{M_*}{M_\odot}) < 10.6$, and high-M$_*$: $10.6 \le \log(\frac{M_*}{M_\odot}) < 11.4$).

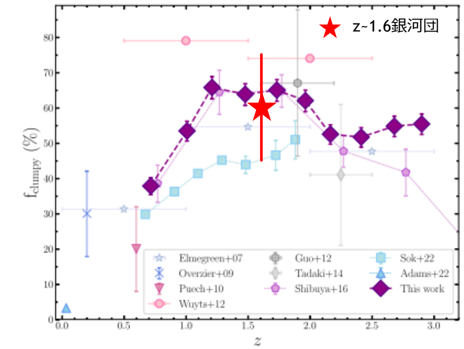

Figure 7. Same as Figure 6, but the fraction of clumpy galaxies is not binned by stellar masses. Also, more studies of clumpy fraction are added to the figure for comparison. Summary of previous studies on clumpy galaxies is presented in Table 2.

←Fig6: clumpy銀河数とredshift (質量別)
z~1-2がピークで、現在に向かって減少（宇宙の星形成史を反映か？）。
Clump同定は波長も手法もサンプルも異なるので定量的な比較は難しい。
- 本論文: rest1600A、off-center clump1つ以上
- Murata: F814W、clump3つ以上
- Guo: rest2500A、flux寄与が8%以上の明るいピクセル群

Fig7: clumpy銀河数とredshift (全体)↑
z>2でフラットという結果。

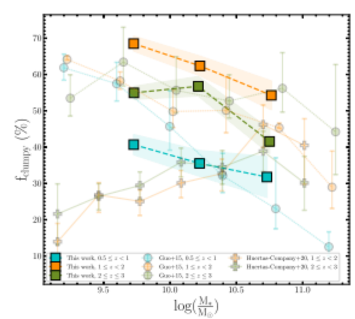

Figure 8. Fraction of clumpy galaxies as a function of stellar mass in different redshift bins. 1σ uncertainties of f_{clumpy} measurements are shown with shaded regions that are calculated by Poisson statistics. Circle and plus data points show reported measurements from Guo et al. (2015) and Huertas-Company et al. (2020), respectively.

Fig8: clumpy銀河数と星質量
どのredshiftでも重いほど少ない傾向。Guo+も同じ傾向だが、H-Cとは合わない。

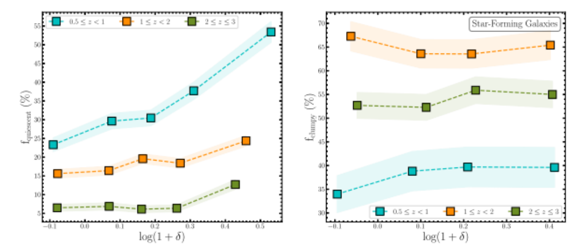

Figure 9. *Left*: Fraction of quiescent galaxies in different bins of redshift and environment. *Right*: Fraction of clumpy galaxies in SFGs as a function of environment in different redshift bins. Error bars (shaded regions) for both panels are estimated by Poisson statistics from the number count of galaxies.

NEW

Fig9: quiescent, clumpy銀河数と数密度
どのredshiftでも、高密度環境 (~銀河群) ほどquiescentは多いが、clumpyは密度によらずほぼ一定。
GOODS-Sのz~1.6銀河団サンプルでも検証 → Fig7の★。Field/group/clusterいずれもclumpy銀河の割合は同程度 → clumpy銀河は環境ではなくdisk不安定等の銀河の内的要因により形成される？
環境に関するサンプルはまだ少なく、今後の広視野高解像度サーベイのデータが待たれる。