K-band Imaging of the Nearby Clumpy, Turbulent Disk Galaxy DYNAMO G04-1

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Abstract

We present a case study of the stellar clumps in G04-1—a clumpy, turbulent disk galaxy located at z = 0.13—from the DYnamics of Newly-Assembled Massive Objects sample, using adaptive optics-enabled K-band imaging (~2.25 kpc arcsec⁻¹) with Keck-NIRC2. We identify 15 stellar clumps in G04-1 with a range of masses from 3.6 × 10^⁶–2.7 × 10^⁸ M⊙, and a median mass of ~2.9 × 10⁷ M⊙. Note that these masses decrease by about half when we apply a light correction for the underlying stellar disk. A majority (12 of 15) of the clumps observed in the Kρ-band imaging have associated components in Hα maps (~2.75 kpc arcsec⁻¹; <Rclump > ~ 500 pc) and appear colocated (Δr ~ 0’1). Using Hubble Space Telescope observations from the Wide Field Camera on the Advanced Camera for Surveys, with the F336W and F467M filters, we also find evidence of radial trends in the stellar properties of the clumps: the clumps closer to the center of G04-1 are more massive (consistent with observations in high-z systems) and appear more red, suggesting they may be more evolved. Using our high-resolution data, we construct a star-forming main sequence for G04-1 in terms of spatially resolved quantities, and find that all regions (both clump and intraclump) within the galaxy are experiencing an enhanced mode of star formation routinely observed in galaxies at high-z. In comparison to recent simulations, our observations of a number of clumps with masses of 10⁷–10⁸ M⊙ are not consistent with strong radiative feedback in this galaxy.

Unified Astronomy Thesaurus concepts: Extragalactic astronomy (506); Galaxy evolution (594); Star formation (1569); Interstellar medium (847); Stellar masses (1614)

1. Introduction

The morphology of star-forming galaxies at 1 ≤ z ≤ 3 is often dominated by giant (~1 kpc) and massive (~10⁶–9 M⊙) clumps that contribute a significant fraction (~20%–30%) of the total system’s star formation. These clumpy structures are consistently observed via tracers of young stars, e.g., in the rest-UV and -optical (Cowie et al. 1995; Elmegreen et al. 2004; Elmegreen & Elmegreen 2005; Elmegreen et al. 2007; Guo et al. 2012) and in ionized gas observations (Genzel et al. 2008). This irregular morphology was initially attributed to galaxy merger activity, and some work examining z > 1 samples has indicated gravitational interactions can drive clumpiness in galaxies (e.g., Puech 2010; Calabrò et al. 2019). However, resolved kinematic studies (e.g., Förster Schreiber et al. 2006, 2009; Genzel et al. 2006; Shapiro et al. 2008; Tacconi et al. 2008; Epinat et al. 2012) have shown that a large fraction of systems (>60%) do not appear to be mergers. Instead, such systems are often identified as orderly rotators, with clumps being thought to form in situ via Toomre instabilities in a gas-rich (f_{gas} ~ 50%–60%) disk (Tacconi et al. 2020).

There is a long-standing concept, motivated largely by simulations (Noguchi 1999; Immeli et al. 2004a, 2004b; Elmegreen et al. 2008; Dekel et al. 2009), that these observed clumps could contribute significantly to the formation of bulges in disk galaxies. The processes that allow for this migration—e.g., decreasing angular momentum due to dynamical friction—require clump in-spiral timescales of the order a few 10⁹ yr. However, the degree to which clumps can contribute to bulge growth via this mechanism depends on their viability, e.g., whether or not they are disrupted by their own stellar feedback within a few orbital times. Observations of normal 1 < z < 3 star-forming galaxies display a range of lifetimes for clumps (100–650 Myr; Zanella et al. 2019; Förster Schreiber & Wuyts 2020), suggesting that some appear sufficiently long-lived to migrate. This is typically the case for higher-mass clumps with M_{clump} > 10⁹ M⊙. If clumps survive long enough to be spiral, one should expect a radial gradient within the galaxy, in particular with age. Evidence for a radial gradient of clump properties has been seen in observations (such as in the SINS and CANDELS galaxies; e.g., Förster Schreiber et al. 2011; Guo et al. 2012; Förster Schreiber & Wuyts 2020; Ginzburg et al. 2021), and these observations appear consistent with simulations (Bournaud et al. 2014; Mandelker et al. 2017; Dekel et al. 2022) where the clumps closer to the galaxy nucleus appear redder, older, denser, and more massive. Other studies at high-z (e.g., Förster Schreiber et al. 2011; Guo et al. 2018; Zanella et al. 2019) report little or only slight evidence of a trend between age and galactocentric radius, although the small-number statistics may have influenced some of these findings. However, there may be some ambiguity in using radial trends as evidence for long-lived clumps, as radial trends are also predicted as a result of inside-out disk formation (Murray et al. 2010; Genel et al. 2012). More recent theoretical work suggests that although clumps may play a role in bulge formation, significant contributions from large gaseous inflows within these disks are likely to be very important for bulge formation as well.
Moreover, galaxies at $z = 1 - 3$ likely experience multiple periods of instability, and one set of clumps need not explain the full mass of the bulges at $z = 0$ (Tacchella et al. 2016).

As the star formation rate (SFR) densities of massive clumps are observed to be very high, stellar feedback effects are predicted to play a crucial role in determining the fate of these clumps and how they contribute to their host galaxies (i.e., in building bulges). Consequently, the stellar masses of clumps are both a strong indicator of their viability and hold important clues regarding the dominant forms of feedback at play. Observations of clumps in $1 < z < 3$ galaxies suggest they are characteristically massive, upwards of $10^{8} - 9 M_{\odot}$ (Elmegreen et al. 2007; Guo et al. 2012; Soto et al. 2017). The true sizes and masses of these clumps remain uncertain, however, due to the inherent resolution limits imposed on observations at high-$z$. Work probing different spatial scales—e.g., from ~1 kpc, as in Förster Schreiber et al. (2011), to a few hundred pc, as in Livermore et al. (2012, 2015)—has consistently found derived clump properties to be resolution-dependent and to vary with spatial scale. This has been supported by investigations of the resolution dependence of clump mass using cosmological simulations (e.g., Huertas-Company et al. 2020; Meng & Gnedin 2020). Dessauges-Zavadsky et al. (2017) examined clumps in both lensed and unlensed star-forming galaxies at $1.1 < z < 3.6$, and found masses ranging from $10^{7} - 10^{9} M_{\odot}$. They have also shown that the limited resolution available for observations of nonlensed systems works alongside clump clustering and projection effects to artificially enhance the derived mass estimates. This is further supported by some studies at lower redshift; Larson et al. (2020) studied clumpy star formation in $z < 0.1$ luminous infrared galaxies (LIRGs) and found the clumps were much less massive ($\sim 10^{5} M_{\odot}$) overall.

Results from numerical work indicate that the details of feedback models have significant impacts on the resulting stellar masses of clumps (Tamburello et al. 2015; Mayer et al. 2016; Mandelker et al. 2017; Dekel et al. 2022). Studies where feedback effects are primarily modeled via radiation pressure and supernovae (e.g., Bournaud et al. 2007, 2014) routinely find long-lived clumps that migrate inward and contribute to bulge growth. Mandelker et al. (2017) found that including radiation pressure increases the surface density and mass thresholds for clumps remaining undisrupted for a few freefall times. Alternatively, Hopkins et al. (2012) used a feedback recipe that included radiation pressure and high photon-trapping fractions. These combined effects produce star-forming clumps that are short-lived (10–100 Myr) and rapidly disrupted, transforming ~10% of their gas into stars (Hopkins et al. 2012). Indeed, Hopkins et al. predict that the distribution of older stellar populations within clumpy star-forming galaxies should be smooth in comparison to the distributions of gas and young stars. Using this feedback prescription, Okloplić et al. (2017) performed a case study on giant clumps in a massive, $z = 2$ disk galaxy and, similarly, found no evidence in their simulations for the net inward migration of clumps, and predicted a smooth, stellar morphology by $z = 1$. Using the NIHAO simulation, Buck et al. (2017) found a similar lack of long-lived clumps, and suggested that the clumps in high-$z$ galaxies were merely the consequence of variable extinction. These simulations are similar in that they both incorporate early radiative feedback with high photon-trapping coefficients in the dust (Hopkins et al. 2012; Stinson et al. 2013).

Because this gas-rich, turbulent mode of star formation occurs primarily in distant galaxies, the effects of redshift must be considered. Distance affects observations in three ways: (1) by generating native limits to resolution with current instrumentation; (2) by creating practical limits to sensitivity; and (3) by shifting spectral features to longer wavelengths, making them impractical to observe with current and near-future instruments. The first two effects—resolution and sensitivity—are assuaged by lensed galaxies (Jones et al. 2010; Livermore et al. 2012, 2015; Dessauges-Zavadsky et al. 2017; Cava et al. 2018). In the vast majority of lensed systems, however, the magnification occurs in only one direction, which complicates structural analysis. Furthermore, observations of lensed galaxies can still be impacted by redshift-related effects. For example, resolved measurements of galaxies at $z > 2$ cannot be undertaken at $\lambda > 500$ nm using current facilities, which significantly challenges efforts to measure the stellar masses of clumps, even in lensed systems.

The optimal wavelength for constraining the masses of clumps is the near-infrared (NIR). The mass-to-light ratios estimated using near-IR observations are less sensitive to degeneracies in extinction, age, and metallicity than are rest-frame visible wavelength observations (Bell & de Jong 2001). High-resolution imaging of very clumpy star-forming galaxies at low redshifts would provide a robust (and highly complementary) viewpoint on the physics of the high-redshift population. Green et al. (2014) presented the DYNamics of Newly-Assembled Massive Objects (DYNAMO) Survey, which is comprised of 95 nearby ($z \sim 0.06–0.08$ & 0.12–0.16) galaxies that closely resemble high-$z$ clumpy systems in terms of their kinematic and star formation properties. The DYNAMO sample has been the subject of a number of follow-on investigations (e.g., Bassett et al. 2014, 2017; Fisher et al. 2014, 2017a, 2017b, 2019; Green et al. 2014; White et al. 2017; Oliva-Altamirano et al. 2018), which test the similarity of these local galaxies to their potential high-redshift counterparts. The most notable exploration of this theme is presented in Fisher et al. (2017a), who used high-resolution H$\alpha$ maps (from the Hubble Space Telescope; hereafter HST) to confirm that DYNAMO galaxies exhibit the same clumpy morphology observed at high redshift. As is the case with massive galaxies at high redshift, a large fraction of DYNAMO systems appear kinematically to be turbulent disks ($\sigma_{\text{gas}} \sim 20–100$ km s$^{-1}$; Bassett et al. 2014; Green et al. 2014; Bekiaris et al. 2016) with high molecular gas fractions ($f_{\text{gas}} \sim 0.2–0.6$; Fisher et al. 2014, 2019; White et al. 2017).

In this paper, we build on the work of Fisher et al. (2017b) by investigating the existence and properties of stellar clumps in G04-1, a galaxy from DYNAMO, using adaptive optics (AO)-enabled NIRC2 $K_p$-band observations.\(^6\) Due to its wealth of previous observations, and its clear classification as a highly star-forming, clumpy, turbulent, gas-rich disk, G04-1 is an ideal candidate for probing the nature of stellar clumps.

This paper is structured as follows. In Section 2, we provide an overview of the target and describe the new NIRC2 and HST observations. In Section 3, we describe the methods we have used for identifying the stellar clumps and calculating the clump properties (such as mass and color) in our imaging data.

\(^6\) In this manuscript, the term “$K$-band” refers to observations taken with the NIRC2 $K_p$ filter ($\Delta \lambda = 1.548 – 2.290\mu m$).
In Section 4, we present our results and discuss them in context. Section 5 summarizes our findings.

Throughout this paper, we assume a cosmology where $H_0 = 67 \text{ km s}^{-1} \text{Mpc}^{-1}$, $\Omega_M = 0.31$, and $\Omega_\Lambda = 0.69$.

2. Observations

2.1. Known Properties of G04-1

Galaxy G04-1 is a member of the greater DYNAMO sample (originally presented in Green et al. 2014; hereafter referred to as DYNAMO-I). DYNAMO is an H$_\alpha$ integral-field spectroscopy survey of local ($z \sim 0.07$ and $z \sim 0.12$) galaxies that have been selected from the Sloan Digital Sky Survey (SDSS; York et al. 2000; Blanton et al. 2017) as being H$_\alpha$-luminous (in the top 1% of H$_\alpha$-emitters in the local universe, based on fiber luminosity; $SFR \sim 11 \ M_\odot \ yr^{-1}$). Located at $z \sim 0.1298$, G04-1 has an integrated stellar mass of $6.47 \times 10^{10} \ M_\odot$ and H$_\alpha$-derived SFR of about $15 \ M_\odot \ yr^{-1}$ (DYNAMO-I). As is the case for G04-1, a large fraction ($\sim 84\%$) of DYNAMO galaxies appear disk-like, and about half are located on the Tully–Fisher relation (Green et al. 2014). Fisher et al. (2017a) produced a surface brightness profile from a high-resolution HST continuum map for G04-1 and found that the system was well fit by an exponential disk + bulge model. Based on the data presented in DYNAMO-I, and on the follow-up kinematic fitting by Bekiari et al. (2016), G04-1 is classified as a turbulent rotating disk ($V_{\text{circ}} = 264 \pm 6 \text{ km s}^{-1}$ and $\sigma_{\text{gas}} = 34 \text{ km s}^{-1}$). Recently, Oliva-Altamirano et al. (2018) have published high-resolution (100–400 pc scale) AO-assisted kinematic maps of DYNAMO galaxies imaged in P$_\alpha$ with Keck-OSIRIS. For G04-1, these authors found an integrated velocity dispersion of $\sigma \sim 51 \text{ km s}^{-1}$. In addition, these authors observed multiple high-dispersion (e$_{\text{max}} \sim 71 \text{ km s}^{-1}$) peaks in the P$_\alpha$ map. G04-1 was also observed to be gas-rich; the CO line fluxes reported by Fisher et al. (2014)—using the Plateau de Bure Interferometer observations of the CO(1-0) transition—estimated a baryonic gas mass fraction of $\sim 31\%$ and a depletion time of about 1.9 Gyr (White et al. 2017). Like many of the systems commonly observed at high-$z$, G04-1 is morphologically clumpy. Using 100 pc resolution HST $H\alpha$ maps, Fisher et al. (2017a) identified 13 massive star-forming clump regions within the galaxy.

2.2. NIRC2 K-band Imaging

G04-1 was observed with the NIRC2 imaging camera on Keck II using WIDECA4 (~0.04″/pixel scale), with laser guide star AO correction and with the $K_p$ filter ($\lambda_c = 2.124 \mu m$). The observations took place on 2016 October 21, as part of the 2016B observing cycle (program W140N2L), for 1.75 hr.

The observations were reduced using fairly standard methods. First, all raw frames were corrected for known bad pixels using the Keck-NIRC2 bad pixel map. Dark current was removed from the science and flat frames by subtracting off a scaled master dark frame. Both lamp-on and lamp-off flat frames (eight each) were recorded on the night of observation, and these frames were median-combined separately (with sigma-clipping) and then subtracted (on-off) to construct a flat field frame. This was divided through all of the science frames to flat-correct the data.

The Keck-NIRC2 images show interference fringes, which are easily detected in flat-corrected frames. We modeled this pattern by first selecting all of the cotemporal science frames within which all of the sources were masked. In most cases, this corresponded with the three frames associated with a single dither pattern. These masked frames were median-combined and scaled (to an appropriate background level) to produce frames that were subtracted off the individual images in order to perform the removal of sky and fringes in a single step. The reduced science frames were individually corrected for distortion effects using IRAF’s DRIZZLE task in combination with the X and Y WIDE camera distortion solutions provided by H. Fu. The image registration and subpixel offsets between the dithered frames were calculated using IRAF’s xREGISTRATION task. Finally, these offset values were used with DRIZZLE once again in order to produce a final coadded image.

Our G04-1 frames contained a ghost image of the Keck primary mirror positioned in the lower-right quadrant of the array. In some cases (~30% of frames), this image—which appeared to be static over the course of the night’s observations—overlapped partially with the dithered position of the galaxy. Where possible (i.e., where the source was in a different quadrant), the region with this feature was left unmasked, so as to remove it during the sky subtraction process described above.

2.3. HST F336W and F467M Observations

We obtained observations (Proposal ID #15069) of G04-1 using the Wide Field Camera on the Advanced Camera for Surveys (WFC/ACS) on the Hubble Space Telescope. The observations were performed using the F336W ($U$) and F467M (Stromgen $b$) medium filters on 2018 February 26 for total integration times of 0.5 and 0.2 hr, respectively. For a further description of the broadband HST images, we refer the reader to Lenkić et al. (2021). The charge transfer effects in the WFC images were mitigated both by placing the target close to the readout edge of the image and by using a postflash to raise the image background to $12 \ e^- \text{ pixel}^{-1}$. All of the images were reduced using the standard HST pipeline and combined using DRIZZLE.

3. Properties of Stellar Clumps in G04-1

3.1. Identification of Stellar Clumps

Clumps were identified in our galaxy maps as follows. First, we constructed a model of our AO point-spread function (PSF) by combining all imaging of all of the point sources from a single observing night (described in more detail in Section 3.3). We then convolved the coadded K-band image with a Gaussian kernel with a width of 10x the FWHM of the PSF (determined by a double Moffat function fit; the details of this derivation are provided in Section 3.3). This corresponds to a kernel size of 1.72. This convolved galaxy image was then divided through the unconvolved image to produce a ratio map from which we identified the stellar clumps.

Next, all of the ratio map pixels above a given threshold—defined as 4x the standard deviation of the intrACLump regions—were identified as peak-value pixels. We then imposed the constraint that all of the peak-value pixels were to represent local peaks in the flux map. Here, we defined the local regions surrounding the peak values as boxes of 10 x 10 pixels—~1 kpc x 1 kpc at $z \sim 0.1$; motivated by the typical clump sizes observed in G04-1 by Fisher et al. (2017b)—in size. If higher-value pixels were found within this local region, the location of

https://www2.keck.hawaii.edu/inst/nirc2/dewarp.html
the flux peak was shifted accordingly. It is emphasized that this technique assumes a minimum separation between the candidate clumps (i.e., the box size). Once the local peaks had been identified, we determined the center of the clump candidates by centroid-fitting a 2D Gaussian + constant to a cutout region of the map surrounding the local peak pixel. We then imposed a final constraint: that all of the clump candidates were to be least as large in size as the FWHM of our combined AO PSF (about 3 × 3 pixels in area). Within G04-1, this process identified 15 stellar clumps. These clumps are shown in the center panel of Figure 1, where the individual clump regions are indicated by the white boxes. In this figure, we also include maps of each of the identified clumps in the HST Hα (from Fisher et al. 2017a), F336W, and F467M data sets.

The number of detected clumps is inherently connected to the detection threshold. Decreasing the detection threshold for clumps to 3σ would increase the number of potential clumps in G04-1 to ∼30 from 15. If we create a more strict definition for clumps, using a threshold of 5σ, this decreases the number of clumps to ∼10. However, we observe that our algorithm fails to identify fainter and smaller clumps (such as IDs = 1 and 9) that are otherwise easily identified by eye. Of course, we acknowledge that this illustrates that there exists a systematic uncertainty in this choice.
We recognize that the clumps we report here in G04-1 do not likely represent a full statistical sample of all of the star clusters in the galaxy. G04-1 is a galaxy with diverse forms of structure, including multiple clumps (as identified in this paper), spiral arms, and a bright nuclear ring. Our aim in this paper is simply to determine whether a rotating disk galaxy with large observed clumps of star formation likewise has larger structures (i.e., clumps) in maps of starlight; and (if so) where these masses are located and to report their corresponding masses. We acknowledge that constructing a catalog of all of the observable structures within the galaxy, spanning a wide range of spatial scales, is beyond the scope of this work.

In summary, we define stellar “clumps” in the present paper as regions within the galaxy disk that (1) represent local flux peaks; (2) are entirely comprised of pixels above a given threshold level (i.e., 4x the background of the disk); and (3) are at least 3 x 3 pixels in size (the FWHM of the AO PSF). A list of the photometric properties of all of the regions meeting these criteria for G04-1 is given in Table 1.

3.2. Determination of Clump Fluxes

We calculated the fluxes of the clumps in two ways. First, we simply integrated the fluxes of all of the pixels within a defined aperture centered on each clump (the apertures were placed at the locations determined in the previous section). In most cases (12 of 15), the clumps identified in our K-band map could be directly associated with the clumps observed in Hα by Fisher et al. (2017a). In these cases, we utilized the apertures described in that work for our flux calculations. In four cases (Clump IDs: 4, 7, 11, and 15), we identified NIR clumps with no obvious Hα counterparts. For these clumps, appropriate apertures were estimated using the observed sizes from the ratio map.

We note that while Clump ID = 7 is well detected in the K-band imaging, it is unique in that it has no observable counterpart (i.e., a feature with a similar morphology and position) in any of the HST data sets presented in this paper. Suspecting that this object is not actually a clump in G04-1, but rather the serendipitous detection of a background infrared source, we have performed a sky coordinate search using the online search tool VIZIER (Ochsenbein et al. 2000), but were unable to find a known object with which we could directly associate this emission. Unable rule out that this feature is indeed a stellar clump—without significant Hα emission—in G04-1, we include it in the analysis and discussion sections that follow.

Next, a local disk background subtraction was performed in order to remove the light contributed from the diffuse disk component. The local disk background value was determined from a region surrounding each clump (an annular aperture of area equal to that of the clump’s aperture). Any nearby clump pixels that fell within this annular region were omitted from the background estimate. This local background component—defined as the mean background value multiplied by the area of the clump’s aperture—was then subtracted off the flux of the clump, \( F_{\text{Kp}} \), to obtain a disk-subtracted flux estimate (\( F_{\text{Kp, diskcorr}} \)). These values are listed in Table 1. In Figure 3 we compare the disk corrected and nondisk corrected clump magnitudes determined from our Keck-NIRC2 K-band and HST F336W and F467M datasets. The near one-to-one relationship between these values indicates that disk light correction effects are independent of clump position. While disk subtraction is typically performed via bulge-disk decomposition methods, attempts (using both the GALFIT and PROFit softwares; Peng et al. 2002; Robotham et al. 2017) to fit a bulge and disk component to the K-band image of G04-1 left substantial structures within the galaxy—i.e., the ring, spiral arms, and bright peaks in fluxes associated with the clumps—that were difficult to model with tolerable residuals. Therefore, we chose to adopt a more clump-centric approach to the removal of the background component.

G04-1’s guide star was used to derive a zero-point value for converting counts/s to fluxes. All of the images of the guide star were reduced using the methods described above, aligned by centroiding, then combined to produce a final image. The star (2MASS J04122098-0555104) has an entry in the Two Micron All-Sky Survey Point-source Catalog (hereafter 2MASS; Skrutskie et al. 2006). We derived a \( Kp \) magnitude for the guide star using its \( Ks \) magnitude (from 2MASS) in combination with the flux ratio of the bandwidths between the

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**Table 1**

| Clump ID | \( K_p \) \((\text{AB mag})\) | \( K_p,\text{diskcorr} \) \((\text{AB mag})\) | \( F_{\text{Kp}} \) \(\times 10^{-14} \text{erg s}^{-1} \text{cm}^{-2}\) | \( F_{\text{Kp, diskcorr}} \) \(\times 10^{-14} \text{erg s}^{-1} \text{cm}^{-2}\) | \( M_* \) \((10^3 M_\odot)\) | \( M_{\text{diskcorr}} \) \((10^3 M_\odot)\) |
|----------|-----------------|-----------------|----------------|----------------|----------------|----------------|
| 1        | 21.08           | 22.77           | 2.01 ± 0.41    | 0.43 ± 0.10    | 2.59 ± 0.79    | 0.55 ± 0.18    |
| 2        | 21.19           | 22.38           | 1.81 ± 0.37    | 0.61 ± 0.13    | 0.85 ± 0.50    | 0.28 ± 0.19    |
| 3        | 20.52           | 21.82           | 3.38 ± 0.68    | 1.02 ± 0.21    | 1.98 ± 1.07    | 0.60 ± 0.30    |
| 4        | 19.70           | 21.26           | 7.22 ± 1.45    | 1.88 ± 0.39    | 12.7 ± 3.31    | 3.31 ± 0.89    |
| 5        | 19.52           | 21.14           | 8.47 ± 1.70    | 1.91 ± 0.40    | 14.9 ± 3.88    | 3.37 ± 0.89    |
| 6        | 21.53           | 23.11           | 1.33 ± 0.27    | 0.31 ± 0.07    | 1.56 ± 0.50    | 0.37 ± 0.12    |
| 7        | 20.72           | 22.07           | 2.80 ± 0.57    | 0.81 ± 0.19    | 3.28 ± 1.06    | 0.95 ± 0.33    |
| 8        | 23.00           | 24.16           | 0.34 ± 0.07    | 0.12 ± 0.04    | 0.36 ± 0.13    | 0.13 ± 0.05    |
| 9        | 22.57           | 23.48           | 0.51 ± 0.11    | 0.22 ± 0.05    | 0.36 ± 0.17    | 0.16 ± 0.08    |
| 10       | 20.85           | 21.47           | 2.50 ± 0.51    | 1.41 ± 0.30    | 2.64 ± 0.91    | 1.49 ± 0.52    |
| 11       | 20.74           | 21.65           | 2.75 ± 0.55    | 1.19 ± 0.25    | 2.90 ± 1.00    | 1.26 ± 0.44    |
| 12       | 20.99           | 22.33           | 2.19 ± 0.44    | 0.64 ± 0.13    | 3.35 ± 0.93    | 0.97 ± 0.27    |
| 13       | 19.22           | 20.28           | 11.2 ± 2.24    | 4.19 ± 0.84    | 5.25 ± 3.45    | 1.97 ± 1.29    |
| 14       | 18.58           | 19.38           | 20.1 ± 4.02    | 9.69 ± 1.94    | 26.6 ± 7.95    | 12.9 ± 3.83    |
| 15       | 20.21           | 21.09           | 4.50 ± 0.90    | 2.00 ± 0.40    | 5.96 ± 1.78    | 2.65 ± 0.79    |

Note:

* The errors on the clump AB magnitudes are approximately 0.24 mag.
Figure 2. Exploring AO PSF effects on clump photometry. In panel (a), the disk-subtracted 1D brightness profile of the combined AO PSF (the black diamonds; see Section 3.3) is shown in comparison with the brightness profile for a typical clump (in green; for clump ID = 2) and the double Moffat best fit to the data (in blue). Panels (b) and (c) illustrate the effects of convolving the observed PSF with a simulated stellar clump. The dashed white circles show the regions defining the photometric aperture and background annulus. These regions have been used to determine the fraction of clump light lost due to the broad wing component of the AO PSF when performing photometry (∼30%).

3.3. AO PSF Effects on Photometry

As described in Section 2.2, our observations of G04-1 incorporate laser guide star AO correction. The shape of the AO PSF is known to vary both in time and with observing conditions, and it is generally modeled as a near diffraction-limited core with a broad, seeing-limited halo component. Except in cases with very high Strehl ratios, a significant fraction of the light is shifted into the wings. The impact of the multicomponent PSF of AO systems may therefore act to systematically reduce the measured fluxes of the clumps. Assuming the standard performance of the Keck AO system, we expect a Strehl ratio of 0.25 in the $K_P$ filter, based on our tip-tilt star magnitude ($R \sim 17$ mag and 2MASS $K_S = 15.7$ mag) and the distance to our target ($r_{\text{offset}} \sim 28\,\text{arcsec}$). The Strehl ratio associated with this set of observations was independently estimated by comparing the imaging of the point sources observed on the same night with a model of the diffraction-limited PSF. We find the Strehl ratios are very similar (0.26, on average) to those supplied by Keck, and therefore a value of 0.25 is used in all of our flux–magnitude calculations. Here, we explore some of the recovery biases associated with performing photometry on our AO-enabled $K_P$-band maps.

In order to increase the signal-to-noise ratio of the faint component, we constructed a model of the AO PSF through a median combination of all of the point sources observed (and scaled by exposure time) on 2016 October 21. These 21 frames correspond to a combined integration time of 1.4 minutes. In Figure 2a, we provide a plot of the azimuthally-averaged 1D surface brightness profile of the combined source (shown as the black diamonds). We find that this AO PSF model from our observations is well fit by a double Moffat function with best-fit parameters (amplitude, core width, and power index) of $(0''91, 0''06, 1''56)$ and $(0''08, 0''13, 1''21)$ for the core and halo components, respectively (shown as the blue solid line). Note: the centering of our double Moffat profile was fixed to the source origin. For comparison, we also include in Figure 2(a) a scaled 1D profile of a characteristic clump (ID: 2) in G04-1. The FWHM corresponding to this double Moffat profile is ∼0''1, which is consistent with that expected in $K$-band at this observing site and given the Strehl ratio assessed above.

Due to image construction effects (i.e., the DRIZZLE algorithm), the empirical PSF of the final coadded Keck-NIRC2 image is likely to be slightly underestimated by this point-source FWHM value. Even so, we expect the difference between these two resolution metrics to be small (<10%). One method of inferring the spatial resolution of this image would be to assess the features observed within the galaxy that appear smaller than the clumps. The dominance of starlight in the disk, however, makes the search for small structures in the galaxy prohibitive. Nevertheless, in the field of the final image of G04-1, we do observe one small source for which we estimate a FWHM of ∼0''15. This provides additional confidence in the FWHM estimate we utilize here to explore the effects of flux loss on our $K$-band clump photometry. We note that our HST F336W ($U$) and F467M ($b$) data sets are also processed by DRIZZLE, and that PSF modeling using TINYTIM predicts the FWHM values in this bands of ∼0''1. Within our final F336W image, we observe a number of point sources in the field surrounding the galaxy. By averaging the on-sky sizes of a few of these sources, we estimate a spatial resolution for our HST data of ∼0''09, which is slightly better in comparison to our $K$-band maps.

We are interested primarily in estimating the fraction of the light originating from stellar clumps that is shifted beyond our flux apertures (i.e., the “light loss”) due to the broad wing component of the AO PSF. We perform a simple simulation of the effects of the PSF on a stellar clump, which we show in Figure 2. Here, we model our clump with a 2D Gaussian function, where the FWHM is set by an average, circularized clump radius (∼0''13 or ∼300 pc) from our sample in Table 1 (Figure 2(b)). We note that many of the clump sizes are

$^5$ TINYTIM is a PSF modeling software package developed by J. Krist and R. Hook. Access to this software is available through the Space Telescope Science Institute HST instrumentation website (https://www.stsci.edu/hst/instrumentation/focus-and-pointing/focus/tiny-tim-hst-psf-modeling).
consistent with the sizes from the HST Hα imaging, and do not suffer from broad components of the PSF. We then convolved this 2D clump with the previously described double Moffat profile in order to mimic the smearing effect of our empirical PSF (see Figure 2(c)). To assess the fraction of light lost, we used a fixed aperture size of $r = 3 \sigma$ (where $\sigma$ is defined by the double Moffat FWHM), and annular radii of $r_{in} = 4 \sigma$ and $r_{out} = 8 \sigma$ (see Figures 2(b) and (c)) to perform flux and background photometry.

After convolution with our AO PSF model, approximately 66% of the clump light remains within the $3 \sigma$ flux aperture, corresponding to a flux/mass correction factor of 1.33. In reality, however, these clumps are embedded within the galaxy disk, and the broad PSF wings also feed stellar light from the surrounding disk back into our clump apertures. This is likely to reduce the flux lost from the clumps. Since we have not included an underlying disk component in our simulation, this correction factor of 1.33 represents an upper limit for the fraction of light lost due to PSF effects.

In our simulation, we find that the per-pixel flux contribution to the local background estimate (determined within the aforementioned annulus) is of an order of $\sim 1\%$ of the amplitude (i.e., the peak pixel value) of the clump. Again, we present this as a rough estimate; the clump clustering and bright structures in G04-1 require estimations of the local disk background to be determined from a range of annuli radii. Moreover, the morphologies of the stellar clumps are observed in our maps to deviate from simple Gaussians. Nevertheless, we note that the clump peak pixel values range between 2–5 $\times$ higher than their corresponding local disk values, suggesting that this light represents a minor contribution to our background estimates.

The authors highlight that the above consideration of the impact of AO correction on the photometry measurements of the clumps within G04-1 is really only possible due to the galaxy’s location at relatively low redshift. The scale length of star-forming clumps in G04-1 is small when compared with the scale length of the disk. This allows us to more cleanly separate the clumps from the underlying disk of the galaxy. This underscores another unique advantage of studying processes at high-z via targets in the DYNAMO sample.

### 3.4. Clump Stellar Masses

It is commonly assumed that stellar mass density varies in lockstep with NIR surface flux density, but we have used our in-hand visible wavelength HST photometry to try to refine our mass estimates using population synthesis models. Integrated and clump-scale mass-to-light ratios for G04-1 were estimated using the stellar population synthesis code GALAXEV, which comprises a library of evolutionary models computed using the isochrone synthesis codes of Bruzual & Charlot (2003). We used spectral energy distribution (SED) models from the Bruzual & Charlot (2003) code base (incorporating their 2011 update), assuming a Chabrier initial mass function (Chabrier 2003). As our goal was to derive mass-to-light ratios for isolated clump regions, we modeled the star formation histories of clumps as simple stellar populations (SSPs; i.e., delta-bursts). The galaxies in DYNAMO (including G04-1) are observed to have metallicities that are slightly subsolar—determined using the $[\text{N} \, \text{II}]/H\alpha$ ratio (Pettini & Pagel 2004) from the SDSS spectra—and a BC2003 SED model consistent with this was chosen from the BaSeL 3.1 spectral library (Bruzual & Charlot 2003).

The clump colors vary to a small degree across the galaxy disk, and we have used the HST data described in Section 2.3 to construct $(U-b)$ maps (using F336W and F467M). Using the apertures defined in calculating the $K_p$-band magnitudes for these maps, we calculated $(U-b)$ color indexes (with and without disk-subtracted magnitudes) for each of the clumps in G04-1. The standard deviation of the clump colors was 0.36 (in AB mag units). Using the BC03 software, we then modeled the evolution of the $K_p$ mass-to-light ratio as a function of observed $(U-b)$ color in order to derive clump-specific mass-to-light ratios. The stellar mass of each clump is then defined as simply the product of the NIR flux and the BC03-derived mass-to-light ratio of the clump. The derived $(U-b)$ clump colors, mass-to-light ratios, and masses are all listed in Tables 1 and 2.
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Figure 3. An assessment of the Keck-NIRC2 $K$-band and HST F336W and F467M filter AB magnitudes (with and without local disk subtraction) for the clumps in G04-1 (with unity slope reference lines shown in red). The near 1-to-1 relationship between the disk-corrected and nondisk-corrected magnitudes indicates that the effects of correction for disk light are independent of clump position in the galaxy.

Figure 4. In this figure, the observed $(U - b; F336W-F467M)$ and $(b - K)$ colors of the clumps in G04-1 are compared to those of two example synthetic stellar populations (generated using GALAXEV and stellar models from Bruzual & Charlot 2003). Here, the positions of the stellar clumps are shown as black stars. The evolutionary tracks of two star formation histories, a simple delta-burst and an exponentially declining SFR (Exp; with an e-folding timescale of $t = 500$ Myr) are provided for reference. The SSP and Exp tracks in red and blue, respectively, include colors with extinction applied, assuming a Calzetti et al. (2000) extinction law. Their counterparts, plotted as gray, do not account for extinction.

Each SSP’s observed magnitudes in our selected filters are evaluated at equally spaced time steps ($\Delta \log$(Age) = 0.05 yr, beginning at $10^7$ yr), and thus we are able to track the color evolution of the burst with time. This provides us with a reasonable metric for estimating the ages of the clumps, using simply their individual $U - b$ colors, which we include on the right-hand axis of Figure 6 (the top panel). We note that the particular age of a clump should be interpreted carefully in terms of the clump lifetime. Bournaud et al. (2014) outline the difficulties associated with accurately measuring the lifetime of clumps based solely on photometric ages. Clumps can have complex star formation histories, and their simulations show that if clumps are long-lived, they will continually rejuvenate (i.e., experience subsequent bursts), meaning that young stars will dominate the age measurement. However, Bassett et al. (2014) report—based on absorption line analysis—an age range of 60–500 Myr for the entire galaxy of G04-1, which is consistent with the clump ages we derive here using stellar population synthesis modeling.

As described above, we derive mass-to-light ratios for the clumps via a method that assumes: (1) that the observed colors reflect those of a single burst of star formation; and (2) that the clump extinction values are similar to those of the disk (e.g., in using disk-subtracted values). Note: the assumption that the clump extinction values are similar to those of the disk is supported by the observations of the $H\alpha$-to-$P_{\alpha}$ flux ratio in G04-1, which is found to be roughly constant (Bassett et al. 2017). Given the observed stability of the $K$-band mass-to-light ratio, the uncertainties associated with estimating stellar masses via $(U - b)$ color are not expected to be significant (e.g., a small variation in clump color is observed across the galaxy). However, as magnitude information is available for clumps in three bands $(U, b,$ and $K_p)$, we can compare the observed $(U - b)$ and $(b - K)$ colors with those generated from stellar population synthesis modeling. This comparison with two distinct star formation histories (a “delta-burst” SSP and an exponentially declining SFR) is shown in Figure 4. In this comparison, we utilize colors calculated from the disk-subtracted magnitudes to minimize $K$-band reddening from the underlying stellar disk in which the clumps are embedded. We incorporate the effects of extinction and reddening via the Calzetti et al. (2000) dust extinction law, assuming $A_{H\alpha} \sim 1 - 1.6$ (derived for G04-1 by Bassett et al. (2017)) and $A_V \sim 1$. The tracks that account for extinction are shown for the SSP and exponential star formation histories in red and blue, respectively. We find that four clumps exhibit both $(U - b)$ and $(b - K)$ colors that map well to those generated by the BC03 SSP modeling. Five clumps are within a magnitude in color from either the SSP or exponentially declining SFR BC03 tracks. Three clumps are vertically offset by $>1$ mag from both tracks, appearing much more red in $(b - K)$ color than predicted by BC03.

These results are challenging to interpret, as it remains unclear how well represented these clump populations are by the simple star formation histories presented here. Indeed, the star formation histories of clumps in high-$z$ turbulent disk galaxies are very poorly constrained. The results from simulation work (e.g., Bournaud et al. 2014) suggest that some clumps may undergo multiple bursts of star formation.
over the course of their lifetime. While actively star-forming clumps are dominated by young stars, they may be holding onto a redder, more evolved stellar population, which might explain them appearing significantly more red. We note, however, that attempts to fine-tune our models for different star formation histories—by using an SSP and an exponential SFR with timescales of 100 < t < 500 Myr) result in an overall range in the average K-band mass-to-light ratio of 0.1–0.15. Further efforts at fine-tuning are likely beyond the scope of this paper. Nonetheless, this shows that the uncertainty of our model results in a small addition to the overall systematic uncertainty associated with stellar mass. This underscores the clear advantage of estimating clump stellar masses using K-band photometry.

4. Results and Discussion

Figure 5 shows a histogram of the full range of clump masses, both before and after background flux subtraction is performed. On average, the subtraction of the local disk component reduces the clump masses by around 50%. The average stellar mass of the clumps before (after) background subtraction for the 15 identified clumps in G04-1 is 5.69 ± 1.8 × 10^5 M_☉ (2.06 ± 0.7 × 10^5 M_☉). The highest- and lowest-mass clumps (Clump IDs 14 and 9) correspond to disk-subtracted masses of 27.0 and 0.36 × 10^5 M_☉, respectively. If we incorporate the correction for light loss due to the wings of the AO PSF (see Section 3.3), the maximum mass for clumps within G04-1 may be as high as 3.6 × 10^6 M_☉. We note that the fractional drop in mass from the background subtraction is consistent across the clumps (i.e., uncorrelated with clump brightness or position in the disk), as shown in Figure 3, in which we directly assess the effect of disk subtraction on the calculated magnitudes of the clumps in the K_p, F336W (U), and F467M (b) data sets.

As described in Section 1, the predictions of the simulations for stellar clump masses in turbulent, clumpy disk galaxies depend quite strongly on the detailed feedback prescription assumed by the model. Observations of galaxy clumps (such as those presented here) are therefore useful for testing these models and for providing insight into the dominant forms of feedback. Strong radiative feedback models predict that clumps of gas are disrupted so quickly that the stellar morphology in these galaxies should be relatively smooth (Hopkins et al. 2012; Oklopić et al. 2017). Indeed, the simulation work by Buck et al. (2017), which incorporates more moderate feedback models, finds little evidence for clumps of stars after 200 Myr. Studies in which feedback effects are modeled as radiation pressure and supernovae, however, predict massive clumps (> 10^8 M_☉). We find that only a small fraction of the clump masses (3 of 15; before disk subtraction) observed in G04-1 are consistent with this mass regime. While the present paper provides data for only a single galaxy, at least in this case the majority of the clumps (both before and after disk subtraction) observed in G04-1 appear to fall in the range 10^6–8 M_☉, which is fairly near the middle of the mass spectrum as observed in high-redshift observations of lensed galaxies and in simulations.

Lenkić et al. (2021) have recently studied the internal color gradients of clumps in DYNAMO galaxies. They find that color gradients of clumps are more commonly consistent with changes in age, rather than extinction. This is different than the explanation of Buck et al. (2017), that clumps in turbulent galaxies are the result of regions of lower extinction. They also find that DYNAMO clump age gradients are consistent with old clumps of stars, with young centers. This is consistent with our results, in which old stellar clumps coexist with high-SFR surface densities. Together, these results give two independent lines of evidence that DYNAMO galaxies contain long-lived clumps of stars.

The total mass of the clumps (after local disk subtraction) is approximately 3.1 × 10^8 M_☉. Using high-resolution HST continuum data, Fisher et al. (2017a) have fit a surface brightness profile for G04-1 and estimated a bulge-to-total ratio of about 11%. Given a total stellar mass of 6.47 × 10^10 M_☉, this corresponds to a current bulge mass of about 7.1 × 10^9 M_☉. If we assume that all of the clumps observed in G04-1 survive sufficiently long to migrate inward, then the total contribution of these clumps to the mass of the bulge would be about 5%. Assuming no further mass growth of the galaxy, this potential contribution increases to 8.54 × 10^8 M_☉, or about 12%, when considering nondisk-subtracted mass estimates. Whether or not the current observations lend support to the notion of bulge building from clump infall clearly depends on the duty cycle of the process, because a single episode of bulge growth from this process would only add to the present bulge incrementally.

4.1. Placing Clump Masses and Sizes in Context

A number of recent observational studies have shown that the star-forming clumps observed in 1 ≲ z ≲ 3 galaxies may not be as massive or large as initially predicted, due to the observational challenges inherent to mapping light in galaxies at high redshift. For example, studies examining systems with strong gravitational lensing have been able to explore clumps at spatial resolutions below 100 pc (e.g., Livermore et al. 2012, 2015; Wuyts et al. 2014) and consistently find smaller clump sizes ranging from 50 pc–1 kpc. In order to explore the effect of resolution on the derived clump properties, Cava et al. (2018) evaluated multiple images of a single galaxy using...
different lensing magnifications (consistent with effective resolutions ranging from 30–300 pc), and found that clump sizes and masses were systematically overestimated at coarse resolutions. Their target galaxy, the Cosmic Snake, has a similar total mass and SFR to ours in this work. They found that, when observed at the finest spatial resolution, the clumps in the Cosmic Snake galaxy have masses ranging from $\sim 10^{-1} - 10^{5.5} M_\odot$, a range quite comparable to ours. Using machine-learning methods to identify the clumps in VELA zoom-in simulations, Huertas-Company et al. (2020) found that observational effects significantly impact the clump properties, leading to the overestimation of stellar mass by a factor of 10. While it is becoming increasingly clear that observational constraints and resolution limits have led to significant ambiguities in the true masses and sizes of clumps, it is difficult to ascertain to what degree these biases have impacted the values we report here for the clumps in G04-1. In this section, we aim to contextualize our work by comparing our findings with similar studies that spatially resolve star formation in galaxies.

Using a combination of HST broadband and narrowband imaging, Bastian et al. (2005) explored star cluster populations in M51. M51 can be taken as a typical star-forming spiral disk, and it is therefore useful in comparison to the extreme star formation in G04-1. They measured masses in complexes of star formation with sizes from $\sim$100 pc to a few hundred parsecs, comparable to the sizes in G04-1. The key difference is the stellar masses estimated for the star-formation associations in M51 are $3\times10^6 - 3\times10^7 M_\odot$, which is multiple orders of magnitude lower than what we observe in G04-1.

Ultraluminous infrared galaxies (U/LIRGs) are a class of local ($z < 0.1$) dusty systems with high-IR luminosities ($L_{\text{IR}} > 10^{11} L_\odot$) and associated SFRs, which are comparable to our target and to galaxies at $z \sim 1 - 3$ (of order $10^{2-3} M_\odot \text{yr}^{-1}$) (Malek et al. 2017; Larson et al. 2020). Looking at the resolved-star formation (via Pa $\alpha$ and Pa $\beta$ line emission) in 48 galaxies from the Great Observatories All-Sky LIRG Survey (GOALS) with HST, Larson et al. (2020) found that while the typical sizes of the clumps in LIRGs were comparable to those observed in DYNAMO ($\sim$100–900 pc), they appear generally less massive ($M_\star \text{median} \sim 5 \times 10^4 M_\odot$) and exhibit individual SFRs that are roughly an order of magnitude lower ($\sim 0.03 M_\odot \text{yr}^{-1}$).

Messa et al. (2019) examined star-forming clumps in 14 galaxies from the Lyman-Alpha Reference Sample (LARS; $z = 0.03 - 0.2$) via UV/optical data from HST. They found that for LARS galaxies—which were selected to be similar to high-$z$ galaxies, based on their H$\alpha$ and UV fluxes—the clump sizes range from 20–600 pc, with a median clump size of about 3–50 pc. While these reported clump sizes are smaller than those seen in DYNAMO ($<R_{\text{clump}} > \sim 500$ pc; Fisher et al. 2017a), it remains unclear whether this indicates a significant difference in clump sizes or whether it is due to the clustering and resolution effects discussed above. For example, the smallest clump sizes reported by Messa et al. (2019) are observed in the lowest-redshift LARS galaxies, where the best resolution of their data ($\sim 10$ pc) is roughly $10 \times$ better than in the HST imaging for G04-1 presented in Section 2.3.

Global system dynamics are closely linked with theoretical formation pathways for star-forming clumps in galaxies, and thus also provide a critical point of comparison (see the discussion in Fisher et al. 2017b). Like other DYNAMO galaxies, G04-1 has been shown to have a well-ordered rotation field, measured both in ionized gas at AO-enabled high spatial resolutions (Oliva-Altimirano et al. 2018) and in stellar kinematics (Bassett et al. 2014). Moreover, Fisher et al. (2017a) show that the starlight profile is consistent with an exponential model. While some fraction of the U/LIRGs are likely to be spirals, the primary dynamical driving mechanism of the bulk of the U/LIRGs is widely considered to be merging (e.g., Larson et al. 2016). This has been shown to be true for the LIRG galaxies in GOALS, where the sample is dominated by interacting systems (Larson et al. 2020). We highlight this important kinematic distinction as it presents an important caveat when comparing the observed properties of clumps in DYNAMO with other local high-SFR samples.

### 4.2. Radial Gradients in Clump Properties

In Figure 6, we show the radial gradients in both clump stellar masses and clump colors. We find that the clumps inside $R < 2$ kpc have average disk-corrected masses of $5.2 \times 10^7 M_\odot$ and average nondisk-corrected F336W–F467M colors of $\sim 0.8$, while the clumps outside this radius appear smaller and bluer, with masses of $9.1 \times 10^6 M_\odot$ and F336W–F467M values of about $\sim 0.6$. The trend in mass is roughly consistent with a log-linear decline in mass with radius. The observable properties of the clumps—e.g., the number, mass, SFR, and age—are fundamental for testing feedback models. In the case of G04-1, there is clear evidence for a clump mass gradient across the galaxy. We have computed Pearson’s correlation coefficients for the three derived quantities in Figure 6, and find $r$-values of $-0.65$, $-0.64$, and $-0.61$ for the clump colors, uncorrected masses, and disk-corrected masses, respectively. This indicates that all three quantities exhibit strong negative gradients across the galaxy disk. This is shown in Figure 6 (bottom panel), which illustrates the radial dependence of clump mass (both before and after disk subtraction). The clumps closer to the galaxy’s nucleus are observed to be significantly—i.e., by more than a factor of ten—more massive than those at the outskirts.

We note that galaxy G04-1 is host to various structural features, including multiple spiral arms and a prominent nuclear ring, which are clearly observed in the top row and central panels in Figure 1. This ring structure appears to be somewhat asymmetric and varies radially in width, due to the existence of bright knots of ongoing star formation and (in some parts) the slight inclination of the galaxy. We have estimated the radial outer edge of this nuclear ring region to be located at a distance of roughly $R_{\text{GC}} \sim 2.2$ kpc (the average value of four measurements made at the cardinal points in the HST H$\alpha$ ratio map image) from the galaxy center. For spatial reference, we include a vertical dashed line denoting the outer edge of this ring region in the panels of Figure 6.

This clump mass gradient in G04-1 could have multiple origins. In particular, it could be due to: (i) the inward migration of clumps while gradually forming more stars; (ii) an inside-out growth of the galaxy disk; or (iii) the Jeans mass being larger at smaller radii. From spatially resolved kinematic maps (using the Keck-OSIRIS observations of the Pa $\alpha$ line; see Oliva-Altimirano et al. 2018), it is known that the gas velocity dispersion in G04-1 declines slightly with radius. While this would argue for a higher Jeans mass near the galaxy center, the declining surface density and age gradient make scenario (iii) unlikely. From Figure 6, it is observed that, from $r = 5$ kpc to $r = 1$ kpc in the disk, clump age increases by about 150 Myr,
the outer edge of the ring region in G04-1 at $z \sim 0.6$, the $0.64$, and $0.61$ for the clump colors, uncorrected masses, and disk-corrected masses, respectively. The vertical gray dashed line represents the outer edge of the ring region in G04-1 at $R_{GC} \sim 2.2$ kpc.

while the overall clump mass increases by about $\sim 10^8 M_\odot$. Lenič et al. (2021) have performed multiband stellar population modeling of the spectral energy distributions of the clumps in G04-1 and found a similar range in clump ages (80–300 Myr). If this variation is entirely due to star formation (e.g., scenario (i)), this would imply that the mean SFR of the clumps during migration should be $\sim 0.7 M_\odot$ yr$^{-1}$. This value is surprisingly consistent with the average clump SFR for this galaxy reported by Fisher et al. (2017a) using H$\alpha$-based measurements ($<\text{SFR}_{\text{clump}} > \sim 0.83 M_\odot$ yr$^{-1}$). This also suggests that an upper limit to the possible mass contributed by the clumps in G04-1 to the bulge—assuming that all clumps complete migration—is of the order of $10^8 M_\odot$ or an addition of roughly $\sim 14\%$ to the bulge mass. The SFR of the clumps is likely to be a more reliable proxy for mass growth than the mass flow rate, as more mass is likely to be lost via feedback than star formation. Notably, the 150 Myr age span observed for the clumps in G04-1 is well matched with the minimum ages predicted for clumps that are able to survive long enough to complete in-spiral to the galaxy center (Förster Schreiber et al. 2011; Guo et al. 2012, 2017; Shibuya et al. 2016; Soto et al. 2017). However, we qualify this simple model by noting that it assumes: (1) that clumps originate in the outskirts of the disk; (2) that the clumps are isolated from the other clumps (i.e., they do not merge); and (3) that all of the clumps within the galaxy survive long enough to complete their migration inward. It remains unclear to what degree these assumptions are reasonable.

We find no clear evidence of a radial dependence on the number density of the clumps; Figure 1 illustrates that stellar clumps are indeed evenly distributed across the disk. Additionally, Figure 6 (top panel) shows that stellar clumps near the nuclear ring appear—albeit to a small degree—consistently more red, suggesting that these stellar populations may be slightly older and more evolved. Fisher et al. (2017a) report the SFRs for these clumps (Section 2, and listed in Table 2), and find higher SFRs for the clumps located near the inner ring (on average $1.6 M_\odot$ yr$^{-1}$) when compared to the arms ($0.5 M_\odot$ yr$^{-1}$).

Our measurements appear to be consistent with observations of clump properties in high-redshift galaxies, as well as with numerical investigations. In their simulations, Mandelker et al. (2014, 2017) and Dekel et al. (2022) find significant gradients in clump properties across the disk. More specifically, the clumps closer to the galaxy center tend to be both more massive and comprised of older stellar populations (i.e., longer-lived). Figure 6 is consistent with the investigation of clump properties at high redshift by Guo et al. (2018), who examined UV-bright clumps in CANDELS galaxies and found significant gradients in both stellar mass—with the inner clumps on average being more massive than the outer clumps by 1–2 orders of magnitude—and color. They also found that the inner clumps appear redder (in $U$–$V$) than those observed in the outskirts of the disks. Förster Schreiber et al. (2011) performed deep HST (NIC2/F160W and ACS/F814W) imaging of clumps in six $z \sim 2$ star-forming galaxies and also found the central clumps to be more massive and older. Positive color and stellar mass gradients were similarly observed by Cava et al. (2018) in the imaging of clumps within the “Cosmic Snake,” a lensed system. Similar mass–radius relations also appear at low redshift: observations of star clusters in local galaxies, such as $z < 0.1$ star-forming spirals (Sun et al. 2016) and the major merger Arp 299 (Randriamanakoto et al. 2019), find that cluster mass increases with decreasing galactocentric radius. Radial trends are often inferred to be an observational basis for clump migration. If the clumps in G04-1 are long-lived, however, and have survived long enough for in-spiral to establish these gradients, then the masses we observe strongly argue against very strong feedback effects (see Section 1).

It is emphasized that the clump mass results shown in Figure 6 are quite robust; these radial trends are certainly not due to uncertainties in the mass-to-light calculations, since our observations use $K$-band imaging, where the mass-to-light ratio is very stable. Moreover, the high spatial resolution in two dimensions allows for an accurate disk subtraction and, therefore, the radial trends cannot be due to background subtraction effects.
we note the following: 

The power-law fit to all of the data points in Figure 7 results in a slope that is remarkably near unity:

$$\log(\Sigma_{\text{SFR}}) = -8.58 \pm 0.21 + 1.041 \pm 0.03 \log(\Sigma_{\text{M_{star}}}).$$

(1)

A separate fit of only the data points associated with the clumps results in a flatter relation:

$$\log(\Sigma_{\text{SFR}}) = -3.69 \pm 3.81 + 0.44 \pm 0.49 \log(\Sigma_{\text{M_{star}}}).$$

(2)

We note that when computing these relations, we omitted a number of very low signal-to-noise ratio data points at large radii in both the Hα and Kp maps, because they were sufficiently near the sky background that their errors were likely to be dominated by systematics from sky subtraction.

Cano-Díaz et al. (2016) used integral-field spectroscopy observations of 306 local galaxies from the CALIFA survey (0.005 < z < 0.03) to derive this relation, and found log(Σ_{SFR}) = −7.95 ± 0.72 log(Σ_{M}). This is significantly less steep than that observed at high-z: Wuyts et al. (2013) used kpc-scale multiwavelength broadband imaging (from CANDELS) and Hα surface brightness profiles (from 3D-HST) for 473 star-forming galaxies (0.7 < z < 1.5), and found log(Σ_{SFR}) = −8.4 ± 0.95 log(Σ_{M}). For reference, we plot both of these observed relations in Figure 7.

Nearly all of the regions within G04-1 directly overlap with the star-forming main sequence relation derived from observations of high-z galaxies. Indeed, the slope and intercept values are remarkably similar. In terms of its integrated properties, G04-1 lies offset from the star-forming main sequence. However, its location at z ∼ 0.1298 results in some ambiguity as to the reason for this offset. For example, one wonders whether G04-1 is a normal, local star-forming galaxy that simply hosts high-SFR clumps (i.e., a scenario where the clumps were completely externally formed and then accreted). From this figure, we infer that this is likely not to be the case. Instead, Figure 7 suggests that all of the regions (both the clump and the intraclump regions) within the galaxy are experiencing an enhanced mode of star formation, more like what is routinely observed in galaxies at high-z.

4.4. Stellar Clumps Are Colocated with Hα

Where possible, we calculate the spatial offsets between the locations of the NIR clumps discussed in the present paper and their counterparts in the Fisher et al. (2017a) Hα maps. On average, the clumps in K-band have centers (determined via centroiding; see Section 3) that are displaced from their corresponding Hα centers (from Fisher et al. 2017a) by about 2.6 pixels (∼0.71). This close alignment of clumps can be visualized in the enlarged clump multiband panels provided in Figure 1. As this average offset between the clumps is very similar to the width of our night’s AO PSF (∼0.3 pixels), we cannot infer whether this offset is indeed real or a manifestation of the PSF associated with our night of data. The clumps in the ring region of G04-1 appear to be more offset from their Hα counterparts than those in the galaxy’s arms. However, as stated in Section 3, a number of the apertures (12, 13, and 14) taken from Fisher et al. (2017b) for the clumps in the ring region of the galaxy required transformation (i.e., rotation and aperture size modification) in order to adequately encompass the K-band flux of the clumps. Indeed, we identify fewer
clumps in the ring of G04-1 than Fisher et al. (2017a). These differences are a likely consequence of the significant amount of additional light contributed from the central disk component in the K-band imaging. This light may be washing out the concentrated light from the individual clumps within the ring and blending structure. These effects would present reasonable explanations for ring clumps exhibiting greater offsets.

In general, the stellar clumps appear to be well aligned with the active star-forming regions observed in the Hα map, implying that these more evolved stellar populations maintain a link with regions of recent star formation. If stellar clumps are long-lived structures, then this would suggest they do not undergo a single burst and then shut off, but that they continue to experience star formation. However, we observe a number of clumps (IDs: 4, 7, 11, and 15) for which we do not observe an obvious Hα component. This is quite interesting because, as seen in Figure 5, we observe that all of the regions in G04-1 associated with clumps exhibit high observed SFR surface densities. This would imply that all of the stellar clumps should be Hα-bright. We have identified two possible scenarios that may explain this. First, the light from these H II regions may be obscured by the existence of a molecular cloud situated along our line of sight. While this would certainly be a very specific situation, it is statistically possible, as typical H II regions are of the order of a few tens of parsecs, and only a few would be required to produce something of the order of the scale of a clump. An alternative scenario would be that these clumps have indeed turned off in terms of their star formation, and are now simply wandering through the gas-rich disk. This second scenario is quite interesting, as numerical simulations (e.g., Bournaud et al. 2014) suggest that clumps massive enough to survive to be long-lived should eventually reaccrete gas from the disk and reignite in star formation. Certainly, more work teasing out the details of these stellar populations is required in order to determine which of these scenarios is more likely.

5. Summary

In this paper, we present a case study of the stellar clumps in a gas-rich, clumpy, turbulent disk galaxy from the DYNAMO sample.

1. We present new K-band imaging of G04-1 using Keck-NIRC2 and HST WFC/ACS observations with the F336W (U) and F467M (Stromgen b) filters.

2. We identify 15 clumps of G04-1 in K-band light that are evenly distributed in mass, ranging from 0.36–27.0 × 10^7 M_☉. These values correspond to Clump IDs 14 and 9, respectively. The subtraction of the local disk component from the clump light results in a drop in the clump mass estimates of around 50%. This corresponds to a median disk-corrected clump mass of ~1.5 × 10^7 M_☉.

3. We find evidence of radial trends in the stellar properties of the clumps. The clumps closer to the galaxy nucleus are observed to be more massive and appear consistently more red, suggesting that these stellar populations may be more evolved. We do not find evidence of a radial dependence on the number density of the clumps.

4. We investigate the relationship between the SFR and stellar mass surface densities using high-resolution maps in Kp (from this paper) and Hα (from HST; presented in Fisher et al. 2017b). A power-law fit to the data results in slope and intercept values—1.041 ± 0.03 and −8.58 ± 0.21, respectively—similar to those derived from populations of high-z galaxies. Indeed, nearly all of the regions in G04-1 appear to be undergoing an enhanced mode of star formation.

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This research makes use of ASTROPy, a community-developed core Python package for Astronomy (Astropy Collaboration, 2013).

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