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UNSTABLE DISKS AT HIGH REDSHIFT: EVIDENCE FOR SMOOTH ACCRETION IN GALAXY FORMATION

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ABSTRACT

Galaxies above redshift 1 can be very clumpy, with irregular morphologies dominated by star complexes as large as 2 kpc and as massive as a few $\times 10^8$ or 10^9 $M_\odot$. Their co-moving densities and rapid evolution suggest that most present-day spirals could have formed through a clumpy phase. The clumps may form by gravitational instabilities in gas-rich turbulent disks; they do not appear to be separate galaxies merging together. We show here that the formation of the observed clumps requires initial disks of gas and stars with almost no stabilizing bulge or stellar halo. This cannot be achieved in models where disk galaxies grow by mergers. Mergers tend to make stellar spheroids even when the gas fraction is high, and then the disk is too stable to make giant clumps. The morphology of high-redshift galaxies thus suggests that inner disks assemble mostly by smooth gas accretion, either from cosmological flows or from the outer disk during a grazing interaction.

Key words: galaxies: formation – galaxies: high-redshift – instabilities

1. INTRODUCTION

In the standard ΛCDM cosmology (Blumenthal et al. 1984), galaxies assemble through hierarchical merging (Davis et al. 1985) and then evolve under a combination of internal and environmental processes. Most of a galaxy's mass comes from mergers with much smaller objects and major mergers are less frequent (De Lucia et al. 2006; Genel et al. 2008). Major and minor mergers tend to transform disks into spheroids and ellipticals (Naab et al. 2007; Bournaud et al. 2007), but if the gas fraction is high enough, then massive and extended disk structures can persist (Robertson et al. 2006; Springel & Hernquist 2005; Robertson & Bullock 2008). Therefore it may be possible, within the hierarchical framework, to explain the formation of disk galaxies with morphologies and kinematics like those observed locally (Governato et al. 2007). It has recently been suggested, however, that a large part of the galaxy mass could instead come from diffuse gas accretion, in particular along cold flows (Dekel et al. 2009a; Ocvirk et al. 2008; Keres et al. 2008). Thus, the buildup of high-redshift galaxies may result from two processes, one hierarchical and the other somewhat smooth. This Letter considers the resolved properties of these galaxies and suggests that the smooth process dominates in a high fraction of cases.

Galaxies are increasingly clumpy with redshift (Conselice et al. 2005). These clumps are not just features in otherwise normal spirals and ellipticals (Cowie et al. 1996; van den Bergh et al. 1996). Most high-redshift galaxies do not have spirals in restframe blue and uv bands, nor do they have bulges or exponential profiles. Usually, a large fraction of their optical light (up to 50%) and luminous mass (up to 30%) is confined to a few kpc-size clumps (Elmegreen & Elmegreen 2005, hereafter EE05). Even the interclump light does not follow a spiral- or exponential-like profile (Elmegreen et al. 2005). Highly aligned clumps have been called *chain* galaxies (Cowie et al. 1996), while rounder systems have been called *clump-clusters* (Elmegreen et al. 2004). Both types could be progenitors of modern spiral disks, viewed with different orientations (Elmegreen et al. 2005; Bournaud et al. 2007, hereafter BEE07). If the clumps are massive enough, then they spiral to the center to make a bulge (Noguchi 1999; Immeli et al. 2004; Elmegreen et al. 2008).

Clumpy galaxies are so frequent at $1 \leqslant z \leqslant 5$, and the clumps evolve so quickly, that most present-day spirals could have had a clumpy phase in their past. Their comoving space density in the Hubble Ultra Deep Field (UDF) is $\sim 10^{-3}$ Mpc^{-3} between $z = 1$ and 4, comparable to the density of spirals in the same redshift range and with the same absolute z_{850} magnitude (Elmegreen et al. 2007). Moreover, the lifetime of the clumpy phase is short, $\sim$ 0.5 Gyr, according to simulations (BEE07). If we consider the ratio of the lifetime of the clumpy phase to the Hubble time as a measure of the fraction of galaxies in that phase at any one time, and multiply the inverse of this ratio by the observed space density of the clumpy systems, then we get a total space density for all galaxies that ever went through the clumpy phase. This total is comparable to the space density of modern spirals.

Several observations suggest that clumps in most chain and clump-cluster galaxies formed inside their disks rather than entered from outside in a merger. First, the distribution of the ratio of axes for the combined population is approximately flat, suggesting that most of the clumpy types are disks viewed in random orientations (EE05). Second, the clumps in chains are highly confined to the average midplanes, which makes external capture unlikely (Elmegreen & Elmegreen 2006a). Third, the masses and sizes of the clumps and the kinematics of clumpy galaxies are consistent with their formation by gravitational instabilities for the observed velocity dispersion (Förster Schreiber et al. 2006; Shapiro et al. 2008; Genzel et al. 2008) and a gas column density comparable to the total in today's inner spiral disks (Elmegreen et al. 2009). Fourth, the height of a clump is comparable to the disk half-thickness, suggesting that both are determined by the gravitational scale length (Elmegreen & Elmegreen 2006a). Fifth, the distribution of relative clump position in a UDF chain is the same as for edge-on clump clusters (Elmegreen 2009). Sixth, the largest clumps have similar masses and ages, unlike the expectation for random capture (Elmegreen et al. 2009). The shape of clumps is another clue to their in situ origin: they are not elongated like spiral arms, so they have to form quickly in a highly unstable disk (Toomre $Q \leqslant 1$). Red interclump colors and a monotonic rise in the rotation curve for one studied case (Bournaud et al. 2008) also suggest the clumps are part of a disk.

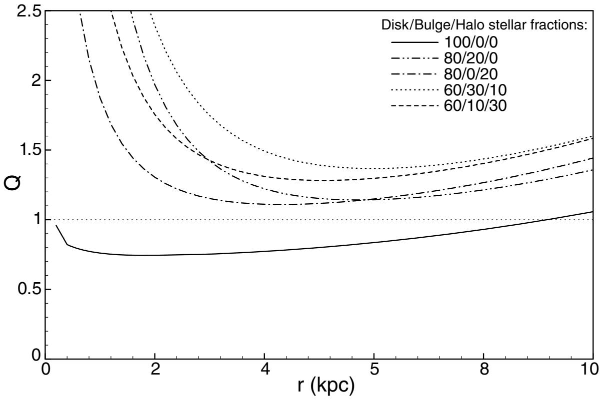

Figure 1. Toomre *Q* parameter for the gaseous and stellar disks, with several assumptions about the stellar mass distribution. The legend indicates the proportion of disk:halo:bulge stars. We assume a uniform surface density for the disk, a Hernquist profile with a scale-length of 600 pc for the bulge, and the same profile with a 6 kpc scale-length for the stellar halo. There is always a dark matter halo, with a core Burkert profile (a cuspy profile would somewhat increase *Q*).

Here we show that giant star-forming clumps require high turbulent speeds and a dense disk with few stars in a spheroid. Simulations of galaxy mergers predict something different: that a large fraction of the stars should end up in a spheroid. Such a spheroid stabilizes the disk and prevents the observed clumps from forming.

2. REQUIREMENTS FOR GIANT CLUMP INSTABILITIES IN PRIMORDIAL GAS DISKS

2.1. High Velocity Dispersions

Typical attributes of UDF clumpy galaxies are a stellar mass $M_* = 6 \times 10^{10}\ M_\odot$ and a disk radius $R = 9$ kpc (EE05). The gas mass fraction f_g (gas-to-total baryon ratio) is not known observationally. An estimate of $f_g \simeq 50\%$ was made by Daddi et al. (2008) in galaxies selected photometrically with the BzK technique (Daddi et al. 2004). We apply this fraction to clumpy galaxies because (1) Daddi et al.'s galaxies are clumpy in the *Hubble Space Telescope* images, and (2) other BzK-selected galaxies have massive clumps like the UDF galaxies (Förster Schreiber et al. 2006; Genzel et al. 2008). Bouché et al. (2007) also support gas fractions around 50%. Much larger gas fractions would exceed the dynamical mass from circular velocities (Bournaud et al. 2008; Daddi et al. 2008). Lower gas fractions would make the clumps too big for the observed velocity dispersion. Thus, we assume $f_g = 50\%$ inside the stellar disk radius, and a gas mass $M_g = M_* = 6 \times 10^{10}\ M_\odot$.

The Jeans length for gravitational instabilities is $\lambda_J = \sigma^2/(\pi G\Sigma)$. For somewhat uniform disks, $\Sigma \sim M_g/\left(\pi R^2\right)$, which gives,

$$\sigma^2 \sim \frac{\lambda_J G M_*}{R^2}. \qquad (1)$$

We consider clumps of size $\lambda_J \sim 500$ pc or larger, so $\sigma \simeq 50$ km s^{-1} for the gas that forms giant clumps. Lower velocity dispersions would give smaller clumps. This result is consistent with Hα observations that suggest a high turbulent speed (Förster Schreiber et al. 2006; Genzel et al. 2008), and with observations of moderately thick disks (Elmegreen & Elmegreen 2006a).

2.2. Dense Disks with Low-Mass Stellar Spheroids

2.2.1. Analytical Constraints on Q

Clumps form by gravitational instabilities if $Q = \sigma\kappa/(\pi G\Sigma) \leqslant 1$. We consider first this requirement on Q for a model in which: (1) $M_g = 6 \times 10^{10}\ M_\odot$ in a disk of radius $R = 9$ kpc with a turbulent speed $\sigma = 50$ km s^{-1}; (2) the total stellar mass of $M_* = 6 \times 10^{10}\ M_\odot$ inside R is partly in a disk of mass $M_{*,D}$, partly in a central bulge of mass $M_{*,B}$ and radius 1 kpc, and partly in a stellar spheroid with $M_{*,H} = 1 - M_{*,D} - M_{*,B}$; (3) there is always a dark halo with a mass $f_D \times (M_g + M_*)$ inside R. We choose $f_D = 0.5$, which means that 2/3 of the mass inside R is baryonic and 1/3 is dark. High-redshift kinematic observations (Daddi et al. 2008; Bournaud et al. 2008) are consistent with this fraction. Modern disk galaxies should be about the same because late infall of dark matter and baryons typically follow each other (Semelin & Combes 2005). Locally, the dark-to-disk ratio f_D is on average 0.6–0.7, and most generally in the 0.3–1.0 range (e.g., Persic & Salluci 1990); our $f_D = 0.5$ choice is thus realistic. We further discuss the influence of this parameter in Section 3.

We compute Q for the combined gas and stellar disks, assuming the stars have about the same velocity dispersion as the gas because both are heated by gravitational instabilities and clump interactions. Then (Wang & Silk 1994)

$$Q(r) \sim \left(\frac{\pi G\Sigma_{\rm gas}}{\sigma_{\rm gas}\kappa(r)} + \frac{3.36 G\Sigma_{\rm star}}{\sigma_{\rm star}\kappa(r)}\right)^{-1}. \qquad (2)$$

When σ is the same for gas and stars, $Q \simeq \sigma\kappa/(\pi G[\Sigma_{\rm gas} + \Sigma_{\rm star}])$. Profiles of $Q(r)$ are shown in Figure 1. When all the stars are in the disk, Σ is high enough and κ is low enough that $Q < 1$ over a large part of the disk. When less than 80% of the stars are in the disk and more than 20% are in a halo or bulge, $Q > 1$ over the whole disk. Then spiral arms can form with star-forming clumps inside, but isolated and round clumps become less likely.

2.2.2. Numerical Simulations

To check these simple Q estimates, we ran models of galaxies with various ratios of disk:bulge:spheroid stellar mass and determined when giant clumps appeared. The mass and size parameters are as in the calculations above, and we start with $\sigma = 50$ km s^{-1} for gas and stars. The simulations were run with higher resolution than in BEE07: 3×10^6 particles each for the stars, gas, and dark matter, and a spatial resolution of 30 pc over the whole disk. The Jeans length is more than ten times larger than the resolution in our initial setup, so numerical fragmentation is avoided (Truelove et al. 1997).

Figure 2 shows the mass distribution of gas and stars at the most clumpy instant for several models. When 100% percent of the stellar mass is initially in the disk, dense round kpc-sized clumps form as in the observed high-redshift galaxies. When 80% of the stars are in the disk and 20% are in a bulge or extended stellar halo, the disk is still somewhat clumpy, but the clumps are not isolated, round, and gravitationally bound—they are bright spots in shearing spiral arms. When 60% or less of the stars lie in the disk and the rest are in a bulge or halo, the disk forms mostly spiral arms (small, low-mass clumps can still form, but only when σ is small).

These models confirm the earlier calculations based on Q alone. The formation of giant clumps requires σ and Σ to be high and κ to be low (Equation (2)). Stars in the rotating disk contribute to Σ and help drive the clump-forming instability,

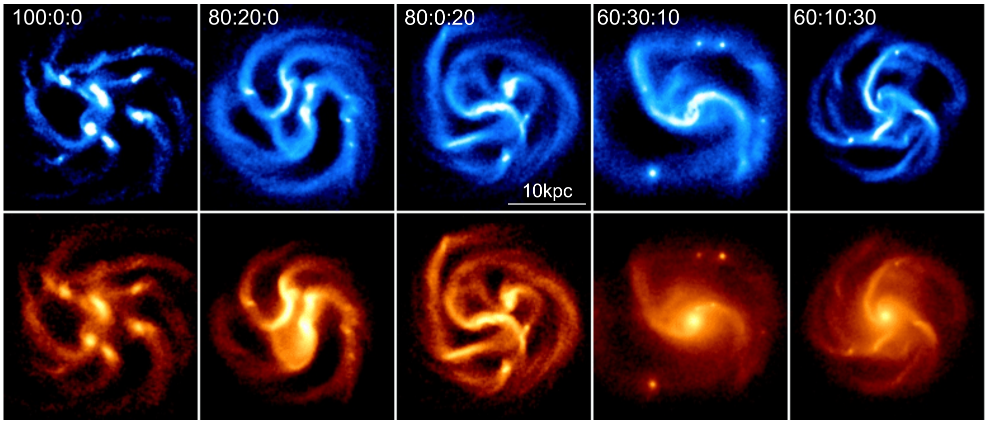

Figure 2. Surface density maps for the gas (top) and stars (bottom), at the most "clumpy" instant seen face-on. The *stellar* mass distribution in the disk:bulge:halo components is varied as in Figure 1; there is always a gas disk and a dark matter halo. All snapshots are shown with the same logscale colorbar.

while stars in the bulge or spheroid increase κ and stabilize the disk. Thus the formation of giant clumps in galaxies with masses and sizes typical of the UDF clump clusters requires that almost all of the stars lie in a rotating disk together with the gas when clump formation starts. If this constraint is not satisfied, then $Q > 1$ and massive clumps do not readily form. If turbulent dissipation decreases σ enough to form clumps when the stellar disk mass is relatively small, then the resulting clumps will have low masses, unlike the observed clumps. Such small clumps are seen in the outer parts of the 60:30:10 and 60:10:30 models in Figure 2. The large observed sizes of clumps at high redshift imply that σ is high, and values of σ higher than that conservatively assumed above would make the formation of clumps even harder to achieve if a stellar spheroid is present, by increasing the Q parameter.

3. CLUMPY GALAXIES IN THE HIERARCHICAL CONTEXT

The clumpy galaxies in the UDF are not obviously mergers, although outer tidal tails and other merger debris could be too faint to see. They are also not former mergers because most of their stars should be confined to a disk in order to get the giant clumps. An important characteristic of disks built by galaxy mergers is that they are embedded in stellar spheroids. For instance, the model spiral galaxy formed in a major merger by Springel & Hernquist (2005) has only $\simeq 25\%$ of its stellar mass in the rotating disk, while $\simeq 50\%$ is in a massive, kpc-sized bulge and $\simeq 25\%$ is in a more extended diffuse stellar halo. Even mergers starting as pure gas rarely end-up with more than 50% of the stellar mass in the disk: Robertson et al. (2006) find that for gas fractions of 0.4 or 0.6, equal-mass mergers end up with only 10% or less of the stars in the disk, the rest being in a bulge and a stellar halo; even initial gas fractions of 80% produce disks containing only 40%–45% of the stellar mass (models DC, EC, FC in Robertson et al. 2006). In the case of minor mergers, their models DCm, ECm, FCm indicate final disk fractions of 60%–75% after a single 8:1 merger, for gas fractions ranging from 0.4 to 0.8. A larger study by (Hopkins et al. 2008) also finds that the fraction of stars in the disk after a single 8:1 minor merger is 70%–85%, depending on the gas fraction and other parameters (e.g., their Figure 12); after a 2:1 merger, the mass in spheroids is equal to or larger than the stellar disk mass. A 1:1 merger ends up with less than one third of the stellar mass in the rotating disk component.

If we consider a typical clumpy galaxy in the UDF and assume that, over the last doubling of its mass, mergers were the dominant growth process, then that growth may have occurred, for example, by a 1:1 major merger or by six successive 8:1 minor mergers. For gas fractions of 50% in the progenitor galaxies (likely for $z \sim 2$; Daddi et al. 2008), such mergers will leave only 20% or less of the stellar mass in the rotating disk, the vast majority being in the bulge and halo. Even higher gas fractions will not allow more than $\sim 50\%$ of the stellar mass in the disk. If we assume that the last mass doubling event was half done by mergers and half by smooth accretion of cold gas, then this requires one 2:1 merger, or three to four mergers of mass ratio 8:1. These will leave only 40%–50% of the stellar mass in the disk, given the various results mentioned above. If we consider mass assembly over longer periods, then the effect of mergers on the bulge and stellar halo will be even more dramatic.

The ubiquity of giant clumps in $z \sim 2$ disk galaxies can be explained most easily if only a small fraction of the stars lie in a bulge or halo before the clumps formed. We found that this fraction should be $< 20\%$, assuming a dark-to-baryonic ratio f_D of 50% inside the optical radius. This ratio f_D should not be much lower in the progenitors of present-day spirals. For a very low f_D of 25% (80% of the mass inside R is baryonic), a slightly more massive stellar spheroid could be present without preventing the formation of large clumps. Still, the fraction of baryons that can be in a bulge or halo remains limited to $\leqslant 30\%$ even in this extreme case (to keep the total dark+stellar spheroid constant). This would allow a relatively higher contribution from mergers in the formation of these galaxies, but it still implies that most of the mass has to enter in a smooth accretion process instead of through major and minor mergers.

The key mechanism is unlikely to be distant interactions that de-stabilize the disk and provoke internal clump formation. Interactions can destabilize a disk (e.g., di Matteo et al. 2008) when the disk was marginally stable, but not when Q was originally high because of a massive spheroid. Furthermore, an interaction-induced process would lead to centrally concentrated star formation because of the associated angular momentum redistribution. This would contradict observations often showing the star-forming clumps at large radii or in ring-like structures in bulge-free disks (Elmegreen & Elmegreen 2006b; Genzel et al. 2008; Elmegreen et al. 2009).

Gas physics and thermal cooling can affect the long-term evolution of clumps, as studied with various hydrodynamic codes by Immeli et al. (2004), Debattista et al. (2006), and Tasker & Bryan (2008). However, in both our simulations and our analytical calculations, thermal cooling is not a critical issue because the turbulent motions in the gas greatly exceed the thermal motions on kpc scales where the instability operates. For our simulations, the turbulent speed is set to a realistic value considering the observed clump sizes, disk thicknesses, and gas velocity dispersions. The medium in which we form clumps thus has realistic properties. Only the small-scale properties of the clumps, such as core formation, molecule formation, and dense cluster formation, all of which are unobserved so far, can be affected by thermal cooling. In a supersonic medium, thermal cooling rates affect the thickness of the shock fronts, but not the overall dissipation rate of the turbulent motions. In this regard, we note that large-scale simulations of supersonically turbulent gas and clump formation require numerical methods that can handle high velocity dispersions in a thermally cold interstellar medium.

If most of the mass assembly of these galaxies came from major and minor mergers, then the disk density would be too low and the shear rate would be too high. Clumps could not form with the masses and sizes typically observed at high redshift. For instance, the merger-produced disk in the model by Robertson & Bullock (2008) is massive and extended, but it only grows spiral arms without giant clumps. The assembly of high-reshift galaxies, with frequent clumpy morphologies, is unlikely to be mostly driven by hierarchical merging of smaller galaxies. Even if minor and major mergers were responsible for only half of the growth, the spheroids would be too massive for disk clumps. The formation of giant clumps points to massive, highly turbulent disks that have relatively small bulges and stellar haloes. This requires that the dominant process of mass assembly be some smooth accretion of cold and diffuse gas. This conclusion is consistent with the recent picture in which young thick disks form by cold flows (Dekel et al. 2009a; Keres et al. 2008) and other types of diffuse gas accretion (Semelin & Combes 2005), bulges form by internal, clump-driven evolution (Elmegreen et al. 2008; Genzel et al. 2008), and the thin disk forms later by further smooth accretion (e.g., Bournaud & Combes 2002). Our result does not imply that mergers do not occur at high redshift, but only that they cannot be the main mechanism for disk assembly.

4. CONCLUSION

The ubiquity of giant clumps in high-redshift disk galaxies constrains the mass distribution and therefore assembly process. Most of the stellar and gas mass should be in a disk, rather than in a bulge or spheroidal halo, in order to get the clump masses, sizes, and morphologies correct. This implies that the assembly is mostly smooth, with only a small fraction through minor and major mergers. Bulges then form as an aftermath of clump evolution. An exception might occur for S0 galaxies, which have much larger stellar spheroids; mergers could have played a more important role in their formation and structure.

Cosmological models including warm dark matter could lead to the required smooth gas accretion because warm dark matter has relatively little substructure. The model by Heller et al. (2007) had a monolithic collapse of gas inside a single halo without hierarchical merging: the gas flow was smooth, and the disk formed through a clumpy phase. Cold dark matter models may also produce smooth gas accretion and satisfy our constraint on the disk mass fraction (e.g., Dekel et al. 2009a; Semelin & Combes 2005; Keres et al. 2008). Recent models by Dekel et al. (2009b) and Agertz et al. (2009) suggest that cold flows could lead to the formation of clumpy galaxies.

Present-day spiral galaxies have apparently evolved through a clumpy phase, and this observation may prove to be a key factor in understanding galaxy assembly and the nature of dark matter.

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