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High-redshift starbursts as progenitors of massive galaxies

Carlos Gómez-Guijarro

AIM, CEA, CNRS, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité, F-91191 Gif-sur-Yvette, France
email: carlos.gomezguijarro@cea.fr

Abstract. Starbursting dust-rich galaxies are capable of assembling large amounts of stellar mass very quickly. They have been proposed as progenitors of the population of compact massive quiescent galaxies at $z \sim 2$. To test this connection, we present a detailed spatially-resolved study of the stars, dust, and stellar mass in a sample of six submillimeter-bright starburst galaxies at $z \sim 4.5$. We found that the systems are undergoing minor mergers and the bulk star formation is located in extremely compact regions. On the other hand, optically-compact star forming galaxies have also been proposed as immediate progenitors of compact massive quiescent galaxies. Were they formed in slow secular processes or in rapid merger-driven starbursts? We explored the location of galaxies with respect to star-forming and structural relations and study the burstiness of star formation. Our results suggest that compact star-forming galaxies could be starbursts winding down and eventually becoming quiescent.

Keywords. galaxies: bulges, galaxies: evolution, galaxies: formation, galaxies: fundamental parameters, galaxies: high-redshift, galaxies: interactions, galaxies: ISM, galaxies: starburst

1. Introduction

Local elliptical galaxies are the largest, oldest, and most massive galaxies in the local universe. How did they form? Already at $z \sim 2$ half of the most massive galaxies appear red and dead, but they are also extremely compact. These are the so-called compact quiescent galaxies (cQGs; e.g., Toft *et al.* 2007; van Dokkum *et al.* 2008), also commonly known in the literature as "red nuggets". The evolutionary pathways of these galaxies to become local ellipticals are thought to be dominated by passive aging and dry minor mergers (e.g., Bezanson *et al.* 2009). How did cQGs at $z \sim 2$ form? What are their progenitors?

Gas-rich major mergers are mechanisms capable of igniting strong nuclear starbursts that create large amounts of stars in compact regions very rapidly. Dusty star-forming galaxies (DSFGs), with the best-studied example being the so-called submillimeter galaxies (SMGs), are the most intense starbursts known with a typical star formation rate (SFR) that goes from hundreds up to thousands of solar masses per year, making them easily observable at far-infrared/submillimeter (FIR/sub-mm) wavelengths at high redshifts (see Casey *et al.* 2014, for a review). Toft *et al.* (2014) proposed a direct evolutionary connection between $z \gtrsim 3$ SMGs and $z \sim 2$ cQGs.

In this text the main results from Gómez-Guijarro *et al.* (2018) and Gómez-Guijarro *et al.* (2019) are outlined, to which the reader is referred for further details.

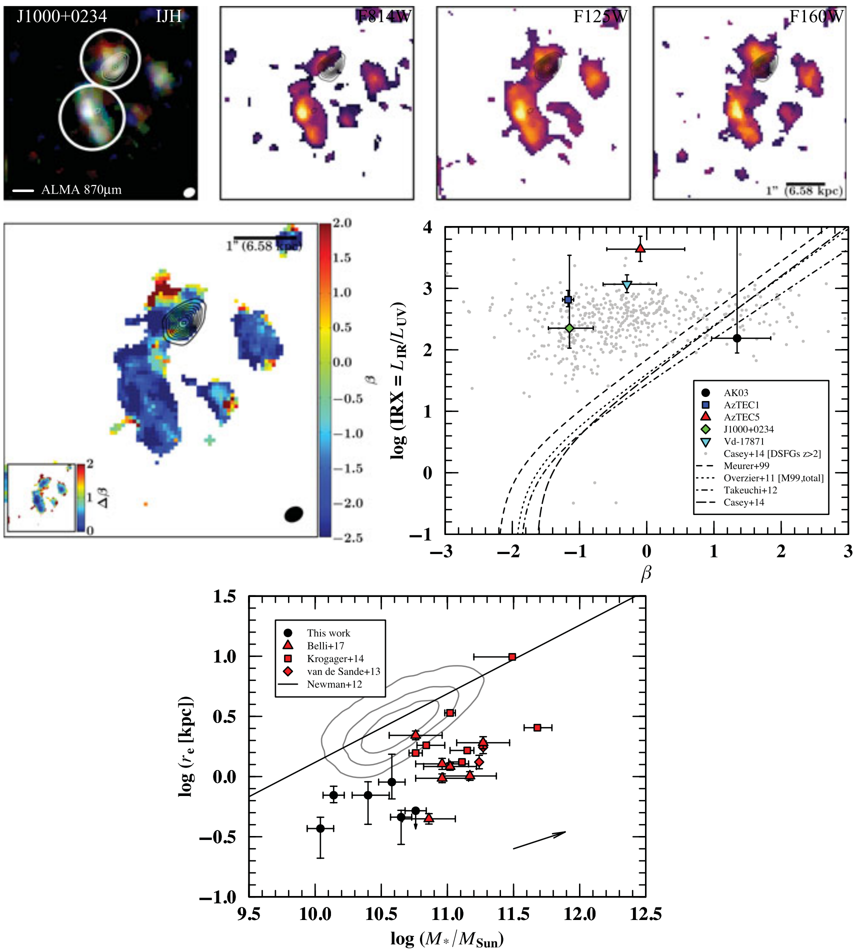

Figure 1. From Gómez-Guijarro *et al.* (2018). Top panel: *HST* images for one of the observed SMGs. ALMA band 7 ($\sim$870 μm) contours are overlayed. Middle left panel: UV continuum slope map for the same SMG. The error map is shown in the bottom left corner. Middle right panel: IRX-β plane. Symbols indicate *HST* photometry performed over the region above the 3σ contour in the ALMA image. Bottom panel: Stellar mass-size plane. SMG sample along with $z \sim 2$ cQGs. The bottom-right black arrow represents the expected evolution of the SMG sample growing in stellar mass via in their current starburst episode and minor merger contribution, and in size via minor mergers.

2. Connecting submillimeter and quiescent galaxies

A very important piece in making such evolutionary connection between $z \gtrsim 3$ SMGs and $z \sim 2$ cQGs comes from the stellar and dust structure of SMGs and how it compares with the proposed quiescent descendants. In the pre-ALMA era, lacking of sufficient spatial resolution very little was known about the dust continuum structure of SMGs and how it related with the stellar structure. In Gómez-Guijarro *et al.* (2018) we tackled this problem and test the evolutionary sequence by targeting a sample of six SMGs, mostly spectroscopically confirmed at $z \sim 4.5$, with both *HST* and ALMA. This study provided a spatially-resolved view of the stars, dust, and stellar mass to have a complete picture of both the unobscured and obscured star formation processes.

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In Fig. 1 one of the SMGs is depicted. While the rest-frame UV stellar emission as seen by *HST* appears extended, irregular and composed of multiple stellar components, the rest-frame FIR dust continuum as seen by ALMA appears very compact (the median effective radius of the sample is 0.70 ± 0.29 kpc), associated but misaligned with respect to just one of the *HST* stellar components (see also e.g., Hodge *et al.* 2016; Elbaz *et al.* 2018). The high spatial resolution of the *HST* observations aid in the deblending of lower resolution ancillary optical–near-infrared data available in the COSMOS field were the sources are located to obtain accurate stellar masses of the multiple stellar components via spectral energy distribution (SED) fitting. The stellar mass associated to the stellar component linked to the FIR dust continuum emission is always higher than that of the companion stellar components. The stellar mass ratios are consistent with minor mergers (the median ratio is 1:6.5, being minor mergers typically defined at 1:3–4). The different stellar components are located at the same redshift. Therefore, we interpreted them as ongoing minor mergers, where most of the star formation is occurring in the ALMA-detected stellar component, which is already the most massive of the system.

The infrared-to-ultraviolet luminosity ratio ($\mathrm{IRX} = \mathrm{L_{IR}}/\mathrm{L_{UV}}$) is known to correlate with the UV continuum slope (β) for star-forming galaxies (SFGs), it is the so-called Meurer relation (Meurer *et al.* 1999, M99 relation hereafter). This relation is very important in galaxy evolution studies because it allows to correct UV-based SFRs when lacking of FIR data. It originates from galaxies becoming redder (higher β) as they become more dust attenuated by dust absorbing UV emission and re-emitting it at infrared wavelengths (higher IRX). This relation also motivates energy balance codes that match the energy of the light absorbed and re-radiated when fitting SEDs. However, DSFGs do not follow this relation. In Gómez-Guijarro *et al.* (2018) we used three *HST* bands to create spatially-resolved β maps for the sources in our sample as shown for one SMG in Fig. 1. Overall, the galaxies appear very blue even in the regions detected by ALMA where the FIR dust continuum is located. The dust attenuation created by the amount of dust in such compact emitting regions is of the order of 100–1000 magnitudes, implying that no emission should escape. The fact that the emission can be seen at rest-frame UV implies that the UV stellar emission and FIR dust continuum emission are physically disconnected and come from different regions, offering a geometrical explanation of the offset of DSFGs with respect to the M99 relation.

In terms of the evolutionary sequence between $z \gtrsim 3$ SMGs and $z \sim 2$ cQGs, thanks to the high spatial resolution observations from *HST* and ALMA that provided a more complete picture of the structure of SMGs, we revisited the stellar mass-size plane in Gómez-Guijarro *et al.* (2018) as shown in Fig. 1. The sample of SMGs and their proposed cQGs descendants at $z \sim 2$ are located in distinct regions of the diagram, but the separation is what is expected given that the SMGs will grow in stellar mass in their current starburst episode and in size due to the observed minor mergers, bringing the location of the populations into agreement and furthering the strength of their evolutionary connection. This evolutionary sequence is also strengthened by recent analysis showing evidence for gaseous rotationally-support disks in some of the SMGs in the sample (e.g., Jones *et al.* 2017; Tadaki *et al.* 2020) and other results on $z \sim 2$ cQGs exhibiting rotationally-supported stellar disks (Newman *et al.* 2015; Toft *et al.* 2017).

3. Investigating the transition from star-forming to quiescent galaxies

SFGs are known to form a tight correlation between SFR and stellar mass, the so-called main sequence (MS) of star formation (e.g., Elbaz *et al.* 2007; Noeske *et al.* 2007), which exhibits a small scatter implying that secular growth must be the dominant mode of galaxy evolution. On the contrary, quiescent galaxies (QGs) are located below the MS. In terms of structure, at fixed stellar mass and redshift SFGs are larger than QGs (e.g.,

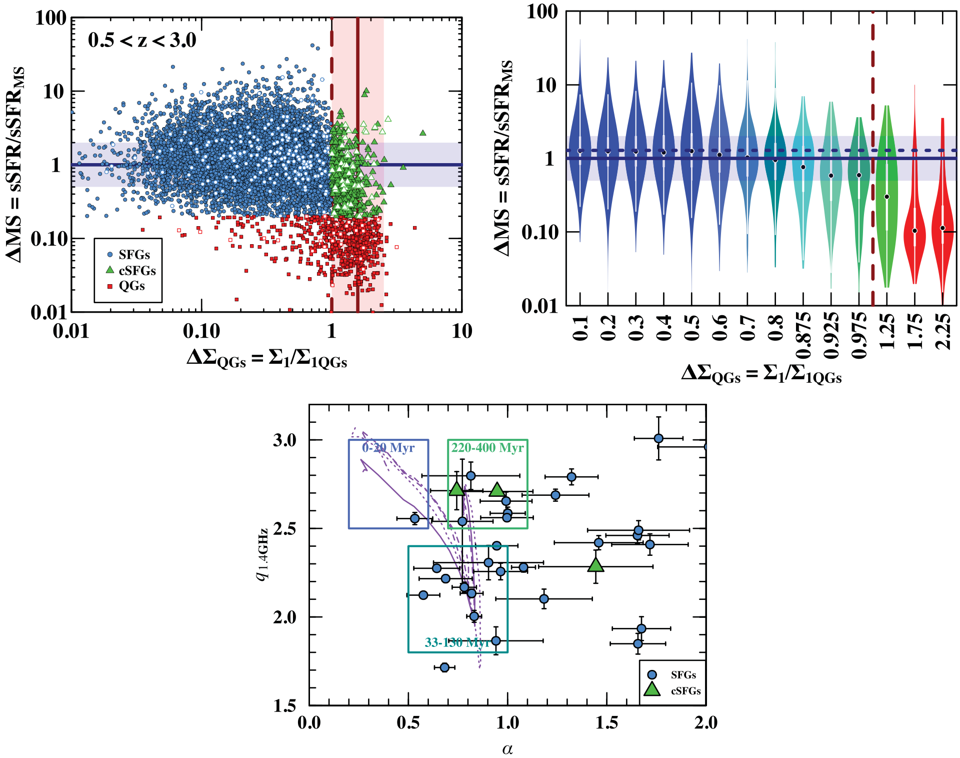

Figure 2. From Gómez-Guijarro *et al.* (2019). Top left panel: ΔMS-$\Delta\Sigma_{\rm QGs}$ plane. Top right panel: Same panel binned in the X axis. Bottom panel: $q_{1.4\rm GHz}$-α plane. (Bressan *et al.* 2002) evolutionary tracks for the age of starbursts are plotted as purple lines.

van der Wel *et al.* 2014). These two fundamental relations of galaxy properties based on star formation and structure put together has lead to several authors to point out that the quenching of star formation and the departure from the MS implies the build up of a central stellar core (e.g., Kauffmann *et al.* 2003; Barro *et al.* 2017). In this context, a population of galaxies arises as the immediate link between the more extended SFG and the more compact QGs, the so-called compact star-forming galaxies (cSFGs; e.g., Barro *et al.* 2013; van Dokkum *et al.* 2015), also commonly refered in the literature as “blue nuggets”. cSFG are galaxies that follow SFG in terms of their location within the fundamental MS of star formation, but that follow the QGs in terms of their location with respect to fundamental structural relations of QGs. Did the build up of the stellar core, formation of cSFGs, and quenching happen slowly as the product of the secular evolution of SFGs, or rapidly requiring a merger-driven starburst episode? In Gómez-Guijarro *et al.* (2019) we studied SFGs and QGs with respect to the MS and structural relations and investigate diagnostic of the burstiness of star formation to address this question.

In Fig. 2 we show individual galaxies in the plane formed by the distance to the MS (ΔMS) at its stellar mass and redshift versus the distance to the compactness selection threshold in the core density based on the structural relation of QGs ($\Delta\Sigma_{\rm QGs} = \Sigma_1/\Sigma_{\rm 1QGs}$) at its stellar mass and redshift (see Barro *et al.* 2017, for details about the compactness threshold). Overall, galaxies become compact before they quench reproducing the L-shape reported by previous studies (e.g., Barro *et al.* 2017; Lee *et al.* 2018). Additionally, we reported two other distinct behaviours in this diagram: 1) as galaxies become progressively more compact (centrally concentrated) they smoothly abandon the

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MS main sequence; 2) while most of them become compact before they quench, some galaxies do go above the MS in the transition. In other words, galaxies seem to die as they increase their stellar core density, but the most important process occurs when crossing the compactness transition threshold with a sub-population going above the MS.

In terms of the diagnostic of burstiness, one we investigated in Gómez-Guijarro *et al.* (2019) was the relation between the FIR/radio ratio ($q \propto L_{\rm IR}/L_{\rm radio}$) and the slope of the power law radio spectrum (α) as a diagnostic for the age of starbursts (Bressan *et al.* 2002; Thomson *et al.* 2014). In Fig. 2 we show the location of individual galaxies in the $q_{\rm 1.4GHz}$-α diagram and divide it into regions of young, middle-age, and old starbursts. Overall, we found a trend of increasing stellar core density with the age of the starburst episode, leading to cSFGs at the old starburst stage, indicating that cSFGs could be starbursts winding down crossing the MS before becoming quiescent.

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