Stellar Population Synthesis of Star-forming Clumps in Galaxy Pairs and Non-interacting Spiral Galaxies

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Abstract

We have identified 1027 star-forming complexes in a sample of 46 galaxies from the Spirals, Bridges, and Tails (SB&T) sample of interacting galaxies, and 693 star-forming complexes in a sample of 38 non-interacting spiral (NIS) galaxies in 8 μm observations from the Spitzer Infrared Array Camera. We have used archival multi-wavelength UV-to-IR observations to fit the observed spectral energy distribution of our clumps with the Code Investigating GALaxy Emission using a double exponentially declined star formation history. We derive the star formation rates (SFRs), stellar masses, ages and fractions of the most recent burst, dust attenuation, and fractional emission due to an active galactic nucleus for these clumps. The resolved star formation main sequence holds on 2.5 kpc scales, although it does not hold on 1 kpc scales. We analyzed the relation between SFR, stellar mass, and age of the recent burst in the SB&T and NIS samples, and we found that the SFR per stellar mass is higher in the SB&T galaxies, and the clumps are younger in the galaxy pairs. We analyzed the SFR radial profile and found that the SFR is enhanced through the disk and in the tidal features relative to normal spirals.

Key words: galaxies: fundamental parameters – galaxies: interactions – galaxies: photometry – galaxies: star formation

Supporting material: machine-readable tables

1. Introduction

Galaxy mergers are key ingredients of galaxy mass growth and morphological transformation in the hierarchical scenario of galaxy formation within the standard cosmological model (Springel et al. 2005; Robertson et al. 2006; Bournaud 2011). Moreover, they were more common at higher redshifts, therefore local galaxy mergers are often used as nearby analogs to improve our understanding of the phenomena involved in high-redshift galaxy evolution.

Since Larson & Tinsley (1978) showed evidence of a burst mode of star formation in peculiar galaxies, several studies have found that galaxy interactions can enhance star formation rates by a factor of 2–3 on average relative to their stellar mass (Bushouse 1987; Kennicutt et al. 1987; Lin et al. 2007; Smith et al. 2007; Li et al. 2008; Knappen et al. 2015). In fact, the most intense star-forming galaxies in the nearby universe, the ultraluminous infrared galaxies, are mostly driven by mergers (Kim & Sanders 1998). One might expect that the most intense star-forming galaxies at the peak of the cosmic star formation rate, z ~ 2 (Madau & Dickinson 2014), would be driven by mergers. However, even using the same data different authors reach different conclusions (Wisnioski et al. 2015; Rodrigues et al. 2017) due to differences in the merger classification criteria.

Resolved star formation studies of nearby interacting galaxies are crucial for identifying which processes are enhancing the star formation. Simulations show that galaxy mergers can produce a loss of axisymmetry, producing gas flows toward the central parts of the galaxies (Mihos & Hernquist 1996), and therefore central starbursts (Di Matteo et al. 2007). However, more recent high-resolution simulations also produced extended star formation due to shock-induced star formation (Barnes 2004; Chien & Barnes 2010), or enhanced compressed modes of turbulence (Bournaud 2011; Powell et al. 2013; Renaud et al. 2014). Analytical models show that tidal disturbances between galaxies perturb the orbits of interstellar clouds, producing high-density, orbiting-crossing zones in the outer disks and tidal tails, presumably triggering star formation (Struck & Smith 2012). However, smoothed particle hydrodynamical (SPH) simulations of pre-merger interacting pairs run by Moreno et al. (2015) find suppressed star formation at radii greater than 1 kpc, compared to isolated galaxies.

Observationally, off-nuclear enhanced star formation is seen in individual cases (Schweizer 1978; Barnes 2004; Wang et al. 2004; Smith et al. 2007, 2010; Chien & Barnes 2010). Larger samples of interacting galaxies are needed to obtain better statistical information on how mergers affect star formation and therefore galaxy evolution. Smith et al. (2016) presented an analysis of ~700 star-forming regions in a sample of 46 galaxy pairs and compared them with those of regions in a sample of 39 normal spiral galaxies, showing that the SFR is proportionally higher for the star-forming regions in galaxy pairs. Zaragoza-Cardiel et al. (2015) found an enhancement in electron density, SFR, and velocity dispersion of ~1000 H II regions in galaxy pairs compared to ~1000 H II regions in non-interacting spirals, analyzing Hα emission, consistent with the picture.
of higher gas turbulence, and higher massive star formation induced by mergers (Bournaud 2011). Nevertheless, neither dust attenuation nor stellar population were analyzed in Zaragoza-Cardiel et al. (2015), because their main purpose was the study of the internal kinematics of H II regions with very high spectral resolution.

Stellar population synthesis can be used to obtain the contribution of the interaction to the star formation in terms of the age of the stellar population, and the star formation rate compared to the stellar mass. A well-defined relationship between the global SFR of star-forming galaxies and their stellar masses, , has been discovered (Brinchmann et al. 2004; Salim et al. 2007); this is known as the star formation main sequence of galaxies. This main sequence evolves with redshift up to (Daddi et al. 2007; Chen et al. 2009), but at a given redshift, the scatter in the SFR for a given stellar mass is consistent at ~0.2 dex (Speagle et al. 2014). Recently, Cano-Díaz et al. (2016) found that the star formation main sequence still holds on kpc scales in a sample of 306 galaxies from The Calar Alto Legacy Integral Field Area survey (CALIFA; Sánchez et al. 2012), claiming that the star formation process is mainly a local process rather than a global one. Similar recent studies concluded that the resolved star formation main sequence holds on kiloparsec scales in nearby galaxies (Abdurrouf & Masayuki 2017; Maragkoudakis et al. 2017) and at redshift (Wuyts et al. 2013; Magdis et al. 2016). Using long-slit optical spectra, Krabbe et al. (2017) performed spatially resolved population synthesis for nine galaxy pairs, and found younger stellar populations than those seen in isolated galaxies. They concluded that this was due to gas flows caused by the interaction.

In the current study we present a stellar population synthesis analysis of the Smith et al. (2016) regions using UV, optical, and IR observations. We then construct the resolved main sequence for the two samples of galaxies and investigate the SFR per stellar mass, the ages of the stellar component, and the spatial extent of the SFR in galaxy pairs. In Section 2 we briefly present the samples, and the photometry of the star-forming complexes that were already presented in Smith et al. (2016). In Section 3 we describe the method used to fit the spectral energy distributions (SEDs) of the clumps to model SED. In Section 4 we present the results of the SED analysis, while in Section 5 we show the analysis of the SFR radial variation. Finally, in Section 6 we provide a discussion and draw our conclusions.

### 2. Data and Clump Photometry

#### 2.1. Data

We have previously presented in Smith et al. (2016) the identification of ~700 star-forming complexes in galaxies from the Spirals, Bridges, and Tails (SB&T) sample (Smith et al. 2007, 2010), and star-forming complexes in a control sample of non-interacting spiral (NIS) galaxies obtained from Kennicutt et al. (2003) and Gil de Paz et al. (2007). We present both samples in Tables 2 and 3. The SB&T sample is composed of pre-merger galaxies pairs chosen from the Arp Atlas (Arp 1966), with velocities <10,350 km s⁻¹ and angular sizes ≥³''; plus NGC 4567/8 and NGC 2207/IC 2163, which are not in the Arp Atlas. The total SB&T sample has 46 pairs, while there are 38 NIS.

The data we used for this study include the GALEX NUV and FUV, Spitzer IRAC 3.6 µm, 4.5 µm, 5.8 µm, 8.0 µm, and Spitzer MIPS 24 µm data used in Smith et al. (2016). For the current study, for the 37 out of 46 galaxy pairs, and the 31 out of 38 spirals with optical Sloan Digitized Sky Survey (SDSS) images we used those data as well. The SDSS ugriz filters have effective wavelengths of 3560 Å, 4680 Å, 6180 Å, 7500 Å, and 8870 Å respectively. The SDSS FWHM spatial resolution is typically about 1''3. For all of the galaxies in the sample, we also carried out clump photometry using the J, H, and Ks maps from the 2MASS survey. These bands have effective wavelengths of 1.25 µm, 1.65 µm, and 2.17 µm, respectively. These images have a spatial resolution of ~4'' (Skrutskie et al. 2006).

To determine total fluxes for the sample galaxies in these filters, we used a set of rectangular boxes that covered the

| Table 1 |
| CIGALE Parameters |
| --- |
| **Free parameters** |
| e-folding time of the old population | 2, 4, 6 Gyr |
| e-folding time of the late starburst population | 5, 10, 25, 50, 100 Myr |
| Mass fraction of the late burst population | 0, 0.2, 0.4, 0.6, 0.8, 0.99 |
| Age of the late burst | 1.5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100, 150, 200, 250, 300, 400, 500 Myr |
| Metallicity | 0.008, 0.02, 0.05 |
| $E(B-V)$ of the stellar continuum light for the young population. | 0.01, 0.2, 0.4, 0.6, 0.7 mag |
| Amplitude of the UV bump | 0, 1, 2, 3 |
| Slope $\delta$ of the power law modifying the attenuation curve | $-0.5, -0.3, -0.1, 0.0$ |
| AGN fraction (just for nuclear regions) | 0.002, 0.2, 0.4, 0.6, 0.8, 0.99 |
| $\alpha$ slope | 1.0, 1.5, 2., 2.5, 3., 3.5, 4. |
| **Fixed parameters** |
| Age of the oldest stars | 13 Gyr |
| Reduction factor for the $E(B-V)$ of the old population compared to the young one | 0.44 |
| IMF | Chabrier (2003) |
| Ionization parameter | $10^{-2}$ |
| Fraction of Lyman continuum photons absorbed by dust | 10% |
| Fraction of Lyman continuum photons escaping the galaxy | 0% |
| System   | Dist (Mpc) | Galaxy     | Morph | logD25 | logR25 | PA (deg) | / (deg) |
|----------|------------|------------|-------|--------|--------|----------|---------|
| Arp24    | 33.1       | NGC 3445   | SABm  | 1.15   | 0.04   | 130.     | 27.9    |
|          |            | PGC 032784 | Sd    | 0.90   | 0.51   | 87.5     | 90.0    |
| Arp34    | 72.5       | NGC 4613   | Sb-c  | 0.51   | 0.02   | 15.      | 18.6    |
|          |            | NGC 4614   | S0-a  | 1.80   | 0.06   | 151.6    | 33.2    |
|          |            | NGC 4615   | Sc    | 1.19   | 0.53   | 120.1    | 76.2    |
| Arp65    | 72.0       | NGC 0909   | SABc  | 0.99   | 0.08   | 120.1    | 34.5    |
|          |            | NGC 0903   | Sab   | 1.12   | 0.25   | 49.8     | 59.3    |
| Arp72    | 53.4       | NGC 5994   | SBc   | 0.78   | 0.29   | 93.3     | 62.5    |
| Arp82    | 59.2       | NGC 2535   | Sc    | 1.29   | 0.31   | 62.5     | 63.1    |
| Arp84    | 55.5       | NGC 5394   | SBb   | 0.87   | 0.21   | 52.7     | 53.3    |
| Arp85    | 12.1       | NGC 5194   | SABb  | 2.14   | 0.07   | 163.0    | 32.6    |
|          |            | NGC 5195   | SBA   | 1.74   | 0.10   | 79.0     | 40.5    |
| Arp86    | 65.9       | NGC 7752   | S?    | 0.96   | 0.30   | 105.5    | 63.8    |
| Arp87    | 104.6      | NGC 3808   | SABc  | 0.97   | 0.11   | 16.5     | 40.1    |
| Arp89    | 31.8       | NGC 2648   | Sa    | 1.50   | 0.47   | 151.0    | 83.7    |
| Arp91    | 34.3       | NGC 5953   | S0-a  | 1.17   | 0.12   | 50.      | 43.9    |
| Arp102   | 104.7      | PGC 060067 | E     | 0.91   | 0.05   | ...      | 35.0    |
| Arp104   | 50.6       | UGC 10814  | SABb  | 1.08   | 0.40   | 170.3    | 71.5    |
| Arp105   | 126.2      | NGC 3561   | S0-a  | 1.23   | 0.00   | 175.0    | 0.0     |
|          |            | UGC 06224  | ...   | 1.07   | 0.23   | 160.7    | 54.9    |
| Arp107   | 141.8      | PGC 032620 | SBab  | 1.20   | 0.11   | 19.7     | 41.8    |
| Arp120   | 14.0       | PGC 032628 | E     | 1.00   | 0.08   | 98.3     | 44.8    |
| Arp178   | 82.5       | NGC 4435   | S0    | 1.48   | 0.15   | 12.2     | 53.6    |
| Arp202   | 47.6       | UGC 10214  | Sc    | 1.16   | 0.32   | 80.2     | 63.7    |
| Arp205   | 24.7       | UGC 06016  | IAB   | 1.26   | 0.15   | 45.5     | 50.6    |
| Arp240   | 101.7      | NGC 3448   | S?    | 1.47   | 0.53   | 64.8     | 79.2    |
| Arp242   | 98.2       | NGC 5257   | SABb  | 1.17   | 0.28   | 85.1     | 62.1    |
| Arp244   | 24.1       | NGC 4676A  | S0-a  | 1.34   | 0.23   | 179.1    | 64.4    |
| Arp245   | 34.0       | NGC 4676B  | S0-a  | 0.99   | 0.17   | 169.0    | 53.3    |
| Arp253   | 28.8       | UGC 0713   | SBD   | 1.09   | 1.01   | 90.0     | 90.0    |
| Arp256   | 109.6      | UGC 0714   | SBm   | 1.12   | 0.53   | 83.1     | 90.0    |
| Arp261   | 28.7       | PGC 052935 | S?    | 1.23   | 0.27   | 146.5    | 58.6    |
| Arp269   | 8.5        | NGC 4485   | I     | 1.30   | 0.18   | 1.7      | 55.2    |
| Arp270   | 29.0       | NGC 3395   | Sc    | 1.20   | 0.26   | 40.5     | 57.8    |
| Arp271   | 40.0       | NGC 5426   | Sc    | 1.49   | 0.40   | 0.5      | 69.7    |
Table 2 (Continued)

| System   | Dist(Mpc)$^a$ | Galaxy   | Morph$^b$ | logD25$^b$| logR25$^b$ | PA(deg)$^f$ | $i$(deg)$^f$ |
|----------|--------------|----------|-----------|-----------|------------|------------|-------------|
| Arp279   | 22.6         | NGC 5427 | SABc      | 1.56      | 0.04       | 178.       | 25.5        |
|          |              | NGC 1253 | SABc      | 1.66      | 0.39       | 84.8       | 68.2        |
|          |              | NGC 1253A| SBm       | 1.00      | 0.19       | 90.3       | 56.4        |
| Arp280   | 14.5         | NGC 3769 | Sb        | 1.45      | 0.50       | 150.2      | 78.3        |
|          |              | NGC 3769 | SBm       | 0.96      | 0.39       | 107.0      | 90.0        |
| Arp282   | 64.9         | IC 1559  | S0-a      | 0.92      | 0.28       | 159.4      | 70.3        |
|          |              | NGC 0169 | Sab       | 1.18      | 0.37       | 92.5       | 69.8        |
| Arp283   | 29.6         | NGC 2798 | Sa        | 1.38      | 0.47       | 160.0      | 84.9        |
|          |              | NGC 2799 | SBD       | 1.25      | 0.58       | 122.5      | 90.0        |
| Arp284   | 38.6         | NGC 7714 | Sb        | 1.34      | 0.14       | 8.4        | 45.1        |
|          |              | NGC 7715 | I         | 1.31      | 0.72       | 78.9       | 90.0        |
| Arp285   | 44.4         | NGC 2854 | SBB       | 1.11      | 0.36       | 52.0       | 68.2        |
|          |              | NGC 2856 | Sbc       | 1.09      | 0.33       | 132.1      | 65.3        |
| Arp290   | 46.5         | IC 0195  | S0        | 1.16      | 0.30       | 134.8      | 77.3        |
|          |              | IC 0196  | Sab       | 1.39      | 0.57       | 9.1        | 90.0        |
| Arp293   | 82.2         | NGC 6285 | S0-a      | 1.03      | 0.28       | 110.0      | 68.1        |
|          |              | NGC 6286 | Sb        | 1.09      | 0.04       | 35.0       | 90.0        |
| Arp294   | 43.6         | NGC 3786 | SABA      | 1.29      | 0.29       | 72.0       | 65.1        |
| Arp295   | 94.2         | PGC072139| Sc        | 1.27      | 0.58       | 37.5       | 80.0        |
| Arp297N  | 139.3        | NGC 5753 | Sab       | 0.73      | 0.10       | 155.0      | 39.3        |
|          |              | NGC 5755 | SBcd      | 0.66      | 0.17       | 102.5      | 48.1        |
| Arp297S  | 70.2         | NGC 5752 | Sbc       | 0.88      | 0.50       | 121.9      | 79.6        |
|          |              | NGC 5754 | SBB       | 1.11      | 0.07       | 96.3       | 32.5        |
| Arp298   | 66.4         | NGC 7469 | Sa        | 1.14      | 0.06       | 126.0      | 30.2        |
|          |              | IC 5283  | Sc        | 1.06      | 0.28       | 105.1      | 60.2        |
| NGC 2207 | 38.0         | NGC 2207 | SABc      | 1.69      | 0.25       | 115.9      | 58.2        |
|          |              | IC 2163  | Sc        | 1.53      | 0.55       | 102.6      | 78.2        |
| NGC 4567 | 13.9         | NGC 4567 | Sbc       | 1.44      | 0.10       | 89.0       | 39.4        |
|          |              | NGC 4568 | Sbc       | 1.63      | 0.36       | 28.6       | 67.5        |

Notes.

$^a$ All the parameters, except the distance, are extracted from Hyperleda database (Makarov et al. 2014) http://leda.univ-lyon1.fr/.

$^b$ From the NASA Extragalactic Database (NED), using $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$, with Virgo, Great Attractor, and Shapley Supercluster infall models.

$^c$ Morphological type.

$^d$ Log of the length the projected major axis of a galaxy at the isophotal level 25 mag arcsec$^{-2}$ in the B-band, D25 in 0.1 arcmin.

$^e$ Log of the axis ratio of the isophote 25 mag arcsec$^{-2}$ in the B-band.

$^f$ Position angle of the major axis of the isophote 25 mag arcsec$^{-2}$ in the B-band (north Eastwards).

$^g$ Inclination.

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observed extent of the galaxy in the images, but avoided very bright stars. These regions included all of the clumps identified in the tidal features (see below for the identification and classification of the clumps). For each image, the sky was determined using rectangular sky regions off of the galaxies without bright stars or other sources. Total fluxes for the individual galaxies in a pair were determined separately and treated separately in the analysis.

2.2. Identification of Clumps

We have identified the clumps in smoothed 8 μm observations from the Spitzer Infrared Array Camera (Fazio et al. 2004). Although the 24 μm filter is considered a better tracer of star formation than 8 μm (e.g., Calzetti et al. 2005, 2007), Spitzer 24 μm images suffer from more artifacts, and have lower native spatial resolution than the 8 μm band. The 8 μm band is also a better choice than Hα to identify star-forming regions in our sample, since our Hα data set is incomplete and inhomogeneous, and the Hα is strongly affected by dust absorption. The UV bands also suffer from extinction, thus a clump search on UV maps may miss the most obscured regions in interacting galaxies and may produce positions that are offset from the peak of the star formation (Smith et al. 2014).

For the identification of clumps, two different Gaussian smoothings were used, one that produces a FWHM resolution of 1 kpc, and another that produces a resolution 2.5 kpc. As described in detail in Smith et al. 2014, clumps were selected automatically from the smoothed images using the Image Reduction and Analysis Facility (IRAF)8 daofind routine (Stetson 1987) using a detection threshold of 10σ above the noise level. The daofind parameters sharplo, sharphi, roundhi were set to 0.1, 1.2, and 2.0, respectively, to allow slightly extended and/or elongated clumps. The images were then inspected visually, to eliminate spurious detections due to artifacts in the images. We show in Figure 1 the identified clumps, (a) 1 kpc, (b) 2.5 kpc, for Arp 82 in all the observed bands.

8 http://iraf.noao.edu
2.3. Photometry of the Clumps

The photometry of the clumps was then performed on the unsmoothed images using the IRAF daophot routine with aperture radii of 1.0 and 2.5 kpc, respectively. The local galactic background was calculated using a sky annulus with an inner radius equal to the aperture radius, and an annulus width equal to 1.2 times the aperture radius. The mode sky fitting algorithm was used to calculate the background level, as the mode is considered most reliable in crowded fields (Stetson 1987). The poorer spatial resolution in the GALEX bands and at 24 μm may lead to a greater clump contribution to the sky background, and thus slightly lower fluxes.

The fluxes were then aperture-corrected to account for spillage outside of the aperture due to the image resolution. For the GALEX, 2MASS, and SDSS images, the aperture corrections were calculated for each image individually. For each image, aperture photometry for 3 to 10 moderately bright isolated point sources was done using our target aperture radius, and then comparing with photometry done within a 1.72 radius. More details on this process are provided in Smith et al. (2016). For the Spitzer data, rather than calculating aperture corrections ourselves we interpolated between the tabulated values of aperture corrections provided in the IRAC and MIPS Instrument Handbooks. We were not able to calculate aperture corrections for the Hα fluxes because of the lack of isolated off-galaxy point sources on the Hα maps. The aperture corrections for Hα are expected to be small because of the

Table 3

NIS Galaxies Sample

| Galaxy     | Dist(Mpc) | Morph | logD25 | logR25 | PA(deg) | #(deg) |
|------------|-----------|-------|--------|--------|---------|--------|
| NGC 24     | 8.2       | Sc    | 1.79   | 0.41   | 44.2    | 70.1   |
| NGC 337    | 22.3      | SBcd  | 1.47   | 0.19   | 158     | 50.6   |
| NGC 628    | 9.9       | Sc    | 2.00   | 0.02   | 87.0    | 19.8   |
| NGC 925    | 9.3       | Scd   | 2.03   | 0.27   | 107.2   | 58.7   |
| NGC 1097   | 16.5      | SBB   | 2.02   | 0.22   | 138.2   | 55.0   |
| NGC 1291   | 10.1      | S0-a  | 2.05   | 0.05   | 156.0   | 29.4   |
| NGC 2403   | 4.6       | SABc  | 2.30   | 0.30   | 126.3   | 61.3   |
| NGC 2543   | 37.4      | Sb    | 1.38   | 0.33   | 52.4    | 66.4   |
| NGC 2639   | 49.6      | Sa    | 1.21   | 0.12   | 140.0   | 44.6   |
| NGC 2841   | 12.3      | SBB   | 1.84   | 0.32   | 147.0   | 65.3   |
| NGC 2857   | 71.0      | Sc    | 1.28   | 0.10   | 90.0    | 38.0   |
| NGC 3049   | 24.1      | SBB   | 1.32   | 0.24   | 27.8    | 58.0   |
| NGC 3184   | 10.1      | SABC  | 1.87   | 0.01   | 117.0   | 14.4   |
| NGC 3344   | 6.9       | Shc   | 1.83   | 0.02   | 150.0   | 18.7   |
| NGC 3353   | 18.5      | SABB  | 1.13   | 0.14   | 75.7    | 45.5   |
| NGC 3367   | 47.6      | Sc    | 1.46   | 0.01   | 70.0    | 11.3   |
| NGC 3521   | 8.0       | SABB  | 1.92   | 0.27   | 162.2   | 60.0   |
| NGC 3621   | 6.5       | SBcd  | 1.99   | 0.39   | 161.2   | 67.5   |
| NGC 3633   | 41.0      | Sa    | 1.08   | 0.43   | 70.6    | 78.9   |
| NGC 3938   | 15.5      | Sc    | 1.55   | 0.01   | 28.0    | 14.1   |
| NGC 4254   | 39.8      | Sc    | 1.70   | 0.03   | 23.0    | 20.1   |
| NGC 4321   | 14.1      | SABB  | 1.78   | 0.04   | 108.0   | 23.4   |
| NGC 4450   | 14.1      | Sab   | 1.74   | 0.16   | 173.0   | 48.7   |
| NGC 4559   | 9.8       | Sc    | 2.02   | 0.34   | 148.3   | 64.8   |
| NGC 4579   | 13.9      | Sb    | 1.70   | 0.12   | 90.2    | 41.9   |
| NGC 4594   | 12.7      | Sa    | 1.93   | 0.24   | 89.5    | 59.4   |
| NGC 4725   | 26.8      | SABA  | 1.99   | 0.14   | 35.7    | 45.4   |
| NGC 4736   | 4.8       | SABA  | 1.89   | 0.06   | 105.0   | 31.8   |
| NGC 4826   | 3.8       | SABA  | 2.02   | 0.29   | 114.0   | 64.0   |
| NGC 5055   | 8.3       | Scb   | 2.07   | 0.22   | 103.0   | 54.9   |
| NGC 5656   | 51.4      | Sab   | 1.10   | 0.15   | 57.2    | 47.6   |
| NGC 6373   | 51.3      | Sc    | 1.01   | 0.17   | 84.2    | 48.9   |
| NGC 6946   | 5.5       | SABC  | 2.06   | 0.02   | 52.0    | 18.3   |
| NGC 7331   | 14.4      | Shc   | 1.97   | 0.39   | 169.7   | 70.0   |
| NGC 7793   | 3.3       | Scd   | 2.02   | 0.24   | 89.5    | 63.6   |
| UGC 04704  | 10.4      | Sd    | 1.56   | 0.98   | 115.2   | 90.0   |
| UGC 05853  | 132.6     | SBc   | 1.10   | 0.82   | 36.9    | 90.0   |
| UGC 06879  | 37.3      | SABC  | 1.15   | 0.53   | 167.5   | 75.5   |

Notes.

a All the parameters, except the distance, are extracted from Hyperleda database (Makarov et al. 2014) http://leda.univ-lyon1.fr/.

b From the NASA Extragalactic Database (NED), using $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$, with Virgo, Great Attractor, and Shapley Supercluster infall models.

c Morphological type.

d Log of the length the projected major axis of a galaxy at the isophotal level 25 mag arcsec$^{-2}$ in the B-band, D25 in 0.1 arcmin.

e Log of the axis ratio of the isophote 25 mag arcsec$^{-2}$ in the B-band.

f Position angle of the major axis of the isophote 25 mag arcsec$^{-2}$ in the B-band (north Eastwards).

g Inclination.

2.3. Photometry of the Clumps

The photometry of the clumps was then performed on the unsmoothed images using the IRAF daophot routine with aperture radii of 1.0 and 2.5 kpc, respectively. The local galactic background was calculated using a sky annulus with an inner radius equal to the aperture radius, and an annulus width equal to 1.2 times the aperture radius. The mode sky fitting algorithm was used to calculate the background level, as the mode is considered most reliable in crowded fields (Stetson 1987). The poorer spatial resolution in the GALEX bands and at 24 μm may lead to a greater clump contribution to the sky background, and thus slightly lower fluxes.

The fluxes were then aperture-corrected to account for spillage outside of the aperture due to the image resolution. For the GALEX, 2MASS, and SDSS images, the aperture corrections were calculated for each image individually. For each image, aperture photometry for 3 to 10 moderately bright isolated point sources was done using our target aperture radius, and then comparing with photometry done within a 17'' radius. More details on this process are provided in Smith et al. (2016). For the Spitzer data, rather than calculating aperture corrections ourselves we interpolated between the tabulated values of aperture corrections provided in the IRAC and MIPS Instrument Handbooks. We were not able to calculate aperture corrections for the Hα fluxes because of the lack of isolated off-galaxy point sources on the Hα maps. The aperture corrections for Hα are expected to be small because of the
Figure 1. GALEX, SDSS, H$_\alpha$, 2MASS, and Spitzer images of Arp 82. (a) Identified clumps at 1 kpc scales. (b) Identified clumps at 2.5 scales. The black circles are clumps in the disk, the white circles are those in the tails, and the gray circles are those in the nucleus.
Table 4

GALEX, Spitzer, SDSS, Hα, and 2MASS Photometry for the Clumps

| Name                                | R.A. (deg) | Decl. (deg) | Galaxy   | NUV (mJy) | NUV err (mJy) | FUV (mJy) | FUV err (mJy) | 3.6 μm (mJy) | 3.6 μm err (mJy) |
|-------------------------------------|-----------|-------------|----------|-----------|--------------|-----------|--------------|--------------|-----------------|
| Arp285_1_sbt_disk_1_0               | 141.00604 | 49.204117   | NGC 2854 | 0.067     | 0.007        | 0.05      | 0.005        | 0.734        | 0.003           |
| Arp285_2_sbt_disk_1_0               | 141.00945 | 49.206093   | NGC 2854 | 0.047     | 0.005        | 0.023     | 0.003        | 0.743        | 0.001           |
| Arp285_3_sbt_disk_1_0               | 141.00803 | 49.200017   | NGC 2854 | 0.07      | 0.008        | 0.048     | 0.006        | 1.207        | 0.003           |
| Arp285_4_sbt_disk_1_0               | 141.01076 | 49.201376   | NGC 2854 | 0.099     | 0.006        | 0.08      | 0.005        | 1.75         | 0.002           |
| Arp285_5_sbt_disk_1_0               | 141.02216 | 49.204905   | NGC 2854 | 0.044     | 0.003        | 0.042     | 0.002        | 0.325        | 0.0008          |
| Arp285_6_sbt_disk_1_0               | 141.0653  | 49.250892   | NGC 2854 | 0.158     | 0.006        | 0.010     | 0.005        | 8.18         | 0.01            |
| Arp285_7_sbt_disk_1_0               | 141.06919 | 49.247372   | NGC 2854 | 0.093     | 0.003        | 0.048     | 0.002        | 8.79         | 0.03            |
| Arp285_8_sbt_disk_1_0               | 141.07527 | 49.241805   | NGC 2854 | 0.0032    | <            | <         | <            | 0.126        | 0.001           |

 relativley high spatial resolution (0′′7–1′′5). If the intrinsic size of a clump is large compared to our aperture radii, our aperture corrections (which assume point sources) may underestimate the true fluxes, particularly for bands with poor intrinsic resolution. For example, some of the clumps may be blends of multiple smaller clumps, with one of our clumps consisting of several smaller components. Alternatively, a clump may be a single physically large object. In these cases, our final fluxes in the filters with the lowest resolution (GALEX and Spitzer 24 μm) may be somewhat underestimated compared to filters with better spatial resolution.

We used the 1 kpc radii clumps to study star formation on smaller scales for the 30 galaxy pairs and 36 NIS galaxies closer than 67 Mpc, and used the 2.5 kpc radii clumps to study star formation on a larger scale in the whole sample; 2.5 kpc is the limiting resolution (6′′ FWHM in GALEX and Spitzer 24 μm). This choice of parameters allowed us to obtain accurate photometry even in the furthest galaxy, Arp107 at 142 Mpc.

In Table 4 we present the photometry for GALEX: NUV and FUV; IRAC: 3.6, 4.5, 5.8, 8.0 μm; MIPS 24 μm; SDSS: u, g, r, i, z; Hα+cont, continuum subtracted Hα, and 2MASS: J, H, K.

### Table 4

| i (mJy) | ierr (mJy) | z (mJy) | zerr (mJy) | Hα + cont (mJy) | Hα + cont err (mJy) | Hα (erg s⁻¹ cm⁻²) | Hαerr (erg s⁻¹ cm⁻²) | Hαcont (erg s⁻¹ cm⁻²) | Hαconterr (erg s⁻¹ cm⁻²) | H (mJy) | Herr (mJy) | I (mJy) | Ierr (mJy) | K (mJy) | Kerr (mJy) |
|---------|------------|---------|-----------|----------------|--------------------|-------------------|-------------------|---------------------|---------------------|---------|------------|---------|------------|---------|------------|
| 0.47    | 0.04       | 0.58    | 0.05      | 0.844          | 0.007              | 2e-14             | 1e-16             | 0.87                | 0.03                | 0.72    | 0.01       | 0.75    | 0.03       |        |            |
| 0.68    | 0.06       | 0.84    | 0.08      | 0.68           | 0.006              | 1.32e-14           | 1e-16             | 1.49                | 0.05                | 1.06    | 0.02       | 0.68    | 0.03       |        |            |
| 1.06    | 0.03       | 1.28    | 0.04      | 0.702          | 0.006              | 9.2e-15            | 1e-16             | 1.82                | 0.03                | 1.58    | 0.02       | 1.64    | 0.02       |        |            |
| 1.51    | 0.05       | 1.88    | 0.08      | 0.84           | 0.01               | 8.4e-15            | 2e-16             | 3.71                | 0.05                | 2.86    | 0.04       | 3.14    | 0.04       |        |            |
| 0.33    | 0.01       | 0.3     | 0.02      | 0.218          | 0.006              | 3e-15              | 1e-16             | 0.25                | 0.03                | 0.3     | 0.02       | 0.26    | 0.03       |        |            |
| 4.47    | 0.07       | 6.1     | 0.1       | 3.44           | 0.01               | 5.81e-14           | 1e-16             | 12.36               | 0.07                | 9.32    | 0.04       | 10.22   | 0.08       |        |            |
| 3.89    | 0.07       | 5.6     | 0.1       | 4.46           | 0.01               | 9.66e-14           | 1e-16             | 11.7                | 0.1                 | 8.8     | 0.08       | 10.45   | 0.08       |        |            |
| 0.118   | 0.008      | 0.13    | 0.01      | 0.048          | <                  | 2.1e-16            | <                 | 0.17                | <                   | 0.3     | 0.02       | 0.24    | 0.02       |        |            |

(This table is available in its entirety in machine-readable form.)

3. SED Modeling

We use the Code for Investigating GALaxy Emission (CIGALE, Noll et al. 2009), python version 0.9, to model and fit the SEDs for each individual clump. CIGALE is based on the assumption of an energy balance between the energy absorbed in the UV, optical, and NIR, and re-emitted by the dust in the MIR and FIR. CIGALE uses the dust emission model of Dale et al. (2014), which is dependent on the relative contribution of different heating intensities, U, modeled by the exponent α in the spatially integrated dust emission $dM_d \propto U^\alpha dU$, where $M_d$ is the dust mass heated by α. http://cigale.lam.fr
radiation intensity $U$ (Dale & Helou 2002). We leave $\alpha$ as a free parameter, and for the nuclear regions we also leave the AGN fraction contribution as a variable (see Table 1), while for the rest of the clumps we set the AGN fraction contribution to zero. To model dust attenuation, CIGALE assumes a combination of dust attenuation curves from Calzetti et al. (2000) and Leitherer et al. (2002) and modifies them by a power law centered at 550 nm, with exponent $\delta$ (free parameter), and adds a UV bump with a specific amplitude (free parameter). We fix the differential reddening, and leave the color excess $E(B-V)$ as a free parameter.

In order to model the plausible recent star formation enhancement in galaxy pairs, we model the star formation history with two decayed exponentials:

$$\text{SFR}(t) = (1 - f_y) \text{SFR}_{0, \text{old}} e^{-t/\tau_1} + f_y \text{SFR}_{0, \text{young}} e^{-t/\tau_2},$$

as described in Serra et al. (2011), where the e-folding times ($\tau_i$), the mass fraction of the recent starburst ($f_y$), and the age ($t_2$) of the recent starburst, are left as free parameters, while the age of the oldest stars ($t_1$) is set (see Table 1 for values). We use the stellar populations of Bruzual & Charlot (2003), considering the Chabrier (2003) initial mass function, and three possible values of metallicity around solar. The CIGALE parameters are summarized in Table 1.

The aforementioned set of parameters yields $3 \cdot 10^6$ models for non-nuclear regions and $1.8 \cdot 10^5$ models for nuclear regions, and then CIGALE performs a Bayesian analysis for each output parameter as described in Noll et al. (2009), resulting in the estimated values and uncertainties given in Table 5. To be sure of the goodness of the fit, we include only the clumps for which the fit of the SED yields $\chi^2_{\text{red}} < 10$. For those clumps with no SDSS observations (27%), the relative uncertainties of the resulting parameters are on average only 2% larger, thus we can include them in the analysis directly with the rest of the clumps. Additionally, since we are interested in the study of recent star formation, we do not consider in the following analysis the clumps and galaxies with no present star formation, i.e., $f_y = 0$.

### 3.1. SED versus Photometric Star Formation Rates

We plot in Figure 2 the instantaneous SFR surface density derived from the SED fitting, $\Sigma_{\text{SFR, SED}}$, versus the photometric SFR surface density derived from UV + IR fluxes, $\Sigma_{\text{SFR, phot}}$, presented in Smith et al. (2016), for all the identified clumps.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Instantaneous SFR surface density derived from the SED fitting, $\Sigma_{\text{SFR, SED}}$, vs. the SFR surface density presented in Smith et al. (2016), $\Sigma_{\text{SFR, phot}}$, color-coded with the probability distribution function derived from the data points, Pr[X]. The solid line represents the variable x-bin size linear fit (Equation 2), while the dashed line represents the one-to-one relation.}
\end{figure}

These points are color-coded with the probability distribution function (PDF) derived from the data points, Pr[X]. We use the same color code in the later figures of this work where we color-coded with the PDF. The variable x-bin size linear fit (solid line) yields:

$$\log(\Sigma_{\text{SFR, SED}}) = (0.96 \pm 0.03) \cdot \log(\Sigma_{\text{SFR, phot}}) - (0.49 \pm 0.08).$$

Thus, using the SFR obtained from the SED fitting is equivalent to using the photometric SFR presented in Smith et al. (2016), since they just differ in a constant shift compared to the one-to-one relation (dashed line in Figure 2). In the following analysis we will use the instantaneous SFR derived from the SED fitting.

### 4. Results

#### 4.1. Integrated Star Formation Main Sequence

We obtained integrated aperture photometry for each galaxy in the SB&T and NIS sample in the same bands as in the clumps. The integrated photometry is presented in Table 6. Then, we used the same set of CIGALE parameters.
For SB&T galaxies (black line in Figure 3), and
\[
\log(\text{SFR}) \left( \frac{M_\odot}{\text{year}} \right) = (0.99 \pm 0.12) \log(M_\odot)(M_\odot)
- (10.4 \pm 1.2),
\]
for NIS (red line in Figure 3). The scatter of the integrated star formation main sequence after removing the average uncertainty by quadrature is 0.47 dex for SB&T galaxies and 0.28 dex for NIS galaxies.

The slopes are in agreement, therefore both samples are in the main sequence of star formation, although the SB&T sample presents more scatter in that relation. The slopes (Equations 3 and 4) are in the range of observed values 0.6–1 (Rodighiero et al. 2011).

### 4.2. Resolved Star Formation Main Sequence

The results are based on 879 clumps from the SB&T galaxies, and 541 clumps from the NIS galaxies.

In Smith et al. (2016) we showed that the clumps in the SB&T galaxies have higher SFRs compared to those in NIS. Here, we explore the differences in the SFR between SB&T and NIS galaxies relative to the stellar mass of the clumps.

We show in Figure 4 the resolved SFR per area, \( \Sigma_{\text{SFR}} \), versus the resolved stellar mass per area, \( \Sigma_{M_\odot} \), Cano-Díaz et al. (2016), Maragkoudakis et al. (2017), and Abdurro’uf & Masayuki (2017) have already shown that the resolved star formation main sequence holds on kiloparsec scales in nearby galaxies. Here, we show that for the clumps in the SB&T galaxies, the

\[
\text{Table 6}
\]

GALEX, Spitzer, SDSS, \( \text{H}_\alpha \), and 2MASS Photometry for the SB&T and NIS Galaxies

| System      | Galaxy     | NUV (mJy) | NUVerr (mJy) | FUV (mJy) | FUVerr (mJy) | 3.6 \( \mu \text{m} \) (mJy) | 3.6 \( \mu \text{m} \)err (mJy) | 4.5 \( \mu \text{m} \) (mJy) | 4.5 \( \mu \text{m} \)err (mJy) |
|-------------|------------|-----------|--------------|-----------|--------------|-----------------|-------------------|-----------------|-------------------|
| Arp120      | NGC 4438   | 4.346     | 0.002        | 2.337     | 0.003        | 510.71          | 0.03              | 301.13          | 0.04              |
| Arp120      | NGC 4435   | 0.707     | 0.0006       | 0.1615    | 0.0009       | 234.41          | 0.01              | 139.42          | 0.01              |
| Arp178      | NGC 5614   | 1.525     | 0.003        | ...       | ...          | ...             | 173.71          | 0.02             | 98.59             |
| Arp178      | NGC 5613   | 0.1235    | 0.0006       | ...       | ...          | ...             | 7.909           | 0.004            | 4.632             |
| Arp181      | NGC 3215   | 0.581     | 0.001        | 0.297     | 0.001        | 27.121          | 0.004            | 17.498          | 0.004             |
| Arp181      | NGC 3212   | 0.4046    | 0.0009       | 0.1702    | 0.0008       | 15.096          | 0.003            | 10.416          | 0.003             |

\[
\text{Table 1}
\]

(3) to derive the integrated SFR and \( M_\odot \) for each galaxy. We plot the star formation main sequence, SFR versus \( M_\odot \), in Figure 3 for the SB&T galaxies in black, and the NIS in red. We perform linear fits to both samples separately, and we obtain:

\[
\log(\text{SFR}) \left( \frac{M_\odot}{\text{year}} \right) = (1.11 \pm 0.13) \log(M_\odot)(M_\odot) - (11.5 \pm 1.2),
\]

Note: Total fluxes have not been corrected for Galactic absorption.

(This table is available in its entirety in machine-readable form.)
resolved star formation main sequence presents a different pattern compared to the clumps in the control sample of NIS on 1 kpc scales. More precisely, there is no linear correlation between SFR and stellar mass, with a large fraction of clumps displaying excess SFR at \( \log(SFR) = 0.5 \pm 0.06 \log(M_\odot/kpc^2) - 6.3 \pm 0.4 \), (5) for 1 kpc scales, and

\[
\log(SFR) \left( \frac{M_\odot}{yr \cdot kpc^2} \right) = (0.78 \pm 0.05) \log(M_\odot/kpc^2) - (8.6 \pm 0.4),
\]

(6)

for 2.5 kpc scales. The scatter of the resolved main sequence of star formation in NIS after removing the mean uncertainty of the estimated SFR by quadrature is 0.41 dex for 1 kpc scales, and 0.36 dex for 2.5 kpc scales, both of these values are larger than those found by Cano-Díaz et al. (2016), but similar to those found by Maragkoudakis et al. (2017) and Abdurro’uf & Masayuki (2017), and larger compared to the scatter of the integrated main sequence of star formation for NIS galaxies. These results, shown as a solid black line in Figure 4 (bottom), show that the resolved star formation main sequence for the two sets of galaxies is different on 1 kpc scales. The slope for the NIS is lower on 1 kpc scales due to the excess of SFR at \( \log(SFR) = 0.5 \pm 0.06 \log(M_\odot/kpc^2) - 6.3 \pm 0.4 \), which is also present in the SB&T clumps on those scales.

We define the SFR\(_{\text{excess}}\) as the difference between the SFR surface density obtained by the SED modeling and the SFR obtained using Equations (5) and (6), and using the stellar mass from Table 5. The SFR\(_{\text{excess}}\) represents the deviation of the observed SFR from that expected, as derived from the resolved main sequence of star formation determined for NIS galaxies. We show in Figure 5 the histograms of the SFR\(_{\text{excess}}\) normalized to the total number of clumps in the SB&T

![Figure 4. Resolved star formation rate per area, S\(_{\text{SFR}}\), vs. resolved stellar mass per area, S\(_{\text{M*}}\), for clumps identified in the SB&T galaxies (top) and NIS galaxies (bottom). The solid black lines are the linear fits with variable x-bin size. The dashed green line is the resolved star formation main sequence from Cano-Díaz et al. (2016).](image-url)
of the SFR excess of the clumps in tails number of clumps in the SB&T galaxies and NIS, respectively. The histograms of the SFR excess of the clumps in tails (black dotted line), in disks (dashed black line), and in the nuclei (blue solid line) of the SB&T galaxies, are normalized to the total number of clumps in the SB&T galaxies. The histogram of SFR excess of the clumps in disks (green dashed line) and in the nucleus (green solid line) of the NIS galaxies, is normalized to the total number of clumps in NIS galaxies. Top: clumps on 1 kpc scales. Bottom: clumps on 2.5 kpc scales. The SFR excess is defined as the difference between the SFR derived from the SED modeling and the one derived from Equations (5) and (6).

galaxies (solid black line), and the number of clumps in NIS (solid red line). We also show the histograms of the SFR excess for the clumps in tails (black dotted line), in the disks (dashed black line), and in the nuclei (blue solid line) of the SB&T galaxies, normalized to the total number of clumps in the SB&T galaxies. We observe that there is a population of clumps with higher SFR excess in the SB&T galaxies, present in the tail, disk, and nuclear clumps, compared to the clumps in NIS on both 1 kpc scales (top), and 2.5 kpc scales (bottom). SFR excesses in the clumps in the SB&T galaxies are probably induced by the interaction, and make a very good case for studying the triggered star formation regime in galaxy pairs. In the higher SFR excess clump population, the star formation is not a local process as claimed by Cano-Díaz et al. (2016), but a global process, because it is affected and enhanced by the interaction.

On 1 kpc scales, the resolved star formation main sequence is different compared to that at 2.5 kpc, even in NIS galaxies, pointing toward a break of the star formation main sequence on smaller scales. Cano-Díaz et al. (2016), Maragkoudakis et al. (2017), and Abdurro’uf & Masayuki (2017) did not observe this break probably because they are based on pixel-to-pixel SED fitting, while in this work we perform the SED fitting based on clumps, i.e., in maximum peaks of star formation, and we subtracted the local galactic background for each clump. Thus, finding an excess of SFR with respect to the stellar mass is more plausible with our method.

We have cross-correlated the two sets of clumps (1 and 2.5kpc) to find 1 kpc clumps within 2.5 kpc clumps. In Figure 6 we show the specific SFR (a), the SFR (b), and the stellar mass (c), at both scales for clumps at 2.5 kpc, which have one or more 1 kpc clump inside them. The specific SFR at 1 kpc scales is larger compared to that of clumps at 2.5 kpc scales, which explains the larger SFR excess found at 1 kpc scales for both SB&T (black circles) and NIS (red circles) samples. On average, the sSFR is four times larger at 1 kpc scales compared to 2.5 kpc scales. This is due to the fact that the SFR is more centrally concentrated than the older stellar population, as can be seen in Figures 6(b) and (c), since the SFR at 1 kpc vs SFR at 2.5 kpc distribution is closer to the one-to-one relation at both scales, while the stellar mass at 2.5 kpc is larger than the stellar mass at 1 kpc scales. In addition, in Figure 6(d) we plot the histograms of the distances between the centers of the clumps at 2.5 kpc and at 1 kpc, Dist_{2.5 kpc-1 kpc} for those 2.5 kpc clumps that have one or more 1 kpc inside them. The distances are dominated by a population of clumps at both scales having the same centers, which means that the strongest star formation tends to occur at the center of large old stellar clumps. However, there is a population of clumps at both scales with very different centers (Dist_{2.5 kpc-1 kpc} > 1 kpc). If we consider that 1 kpc clump are being within a 2.5 kpc clump if at least half of it is completely inside, just 47 clumps at 2.5 kpc have two or more 1 kpc clumps within them, out of 381 2.5 kpc identified clumps. Then, we can neglect the effect of blending.

4.3. Recently Induced Star Formation

In order to explore the possible connection between the higher SFR excess of clumps in the SB&T galaxies and their recent interaction history, we compared the derived age of the recent burst (t_{2} in Equation (1)) from the SED fitting with the SFR excess. We plot in Figure 7 the SFR excess versus the age of the recent burst for clumps in the SB&T galaxies (top) and in the NIS galaxies (bottom), color-coded with the PDF. Figure 7 shows that the SFR excess depends on the age of the recent burst of star formation; the younger the recent burst, the higher the SFR excess. Additionally, the density of data points shows that the SB&T galaxies have a population of clumps that have a younger recent burst of star formation, notably at log(Burst Age) ~ 1.9, and also at log(Burst Age) < 1, compared to the NIS galaxies. Therefore, the triggering of the SFR excess in the SB&T galaxies is evidently due to a recent event such as an interaction with a companion galaxy.

Histograms of the age of the recent burst (Figure 8) show that there is a population of clumps in the SB&T galaxies (solid black lines) with smaller ages compared to the NIS galaxies (solid red line) on both scales. Younger recent burst ages are found in the tails (black dotted line), the disks (dashed black line), and the nuclei (blue solid line) of the SB&T galaxies. These results show that there are more recent bursts of star formation in the clumps of the SB&T galaxies induced by the interactions, which enhance the observed SFR excess.

5. SFR Radial Profile

The SB&T sample of galaxies is composed of galaxy pairs in an early-intermediate stage of the merger process, while advanced mergers are excluded. Therefore, the distortions are small enough to be able to study the SFR radial profile for the clumps in the SB&T sample, in order to see the radial variation of the SFR enhancement.

We normalized the galactocentric radius of each identified clump by the isophotal radius at 25 mag arcsec^{-2} in the B-band, in order to compare all the galaxies from both samples together. We obtained the inclinations, position angles, and
lengths of the major axis at the isophotal level $25$ mag arcsec$^{-2}$ in the B-band, from the Hyperleda database (Makarov et al. 2014),\footnote{http://leda.univ-lyon1.fr/} for each galaxy (see Tables 2 and 3). We show in Figure 9 the isophotal radius at $25$ mag arcsec$^{-2}$ in the B-band, $R_{25}$, versus the effective radius in the J-band from 2MASS, $R_{\text{eff}}$, for SB&T and NIS galaxies. We obtained J-band $R_{\text{eff}}$ from the 2MASS All-Sky Extended Source Catalog (Skrutskie et al. 2006). Since the surface brightness is independent of distance, the choice of isophotal or effective radius is just affected by a constant factor, thus the selection of the isophotal radius does not affect the results presented below.

For the SB&T galaxies, we obtained those parameters for each individual galaxy and associate each clump with one of the galaxies to normalize the galactocentric radius of each clump with the corresponding isophotal radius of his galaxy.

The Galaxy column in Table 4 refers to the specific galaxy from the galaxy pair the clump is associated with.

Several studies show that the spatial distribution of the SFR in spirals approximately follows an exponential profile (Hodge & Kennicutt 1983; Athanassoula et al. 1993; Ryder & Dopita 1994; Koopmann et al. 2006). Thus, we plot in Figure 10 (top) the SFR surface density, $\Sigma_{\text{SFR}}$, of the clumps in disks from the NIS galaxies, versus the galactocentric radius normalized by the isophotal radius at $25$ mag arcsec$^{-2}$ in the B-band, $R_{\text{gal}}/R_{25}$, color-coded with the PDF, and we perform a variable $x$-bin size fit to the data, obtaining

$$\log(\Sigma_{\text{SFR}}) = (-1.42 \pm 0.10) R_{\text{gal}}/R_{25} - (2.04 \pm 0.06).$$

The variable $x$-bin size fit allows us to weight by the density of data points, assuming a constant number of data points in each bin.

In the middle panel of Figure 10 we plot $\Sigma_{\text{SFR}}$ versus $R_{\text{gal}}/R_{25}$, of the clumps in the disks and tails of the SB&T...
Figure 7. SFR excess vs. the age of the recent starburst, color-coded with the PDF. The figure displays clumps in the SB&T galaxies (top) and in the NIS galaxy sample (bottom). The SFR excess is defined as the difference between the SFR derived from the SED modeling and that derived from Equations (5) and (6).

Figure 8. Age of the recent starburst histograms for clumps in the SB&T galaxies (solid black line), and for clumps in the NIS galaxies (solid red line), normalized by the total numbers of clumps in the SB&T galaxies and the total number of clumps in the NIS galaxies, respectively. Top: clumps at 1 kpc scales. Bottom: clumps at 2.5 kpc scales. The black dotted lines are the age of the recent starburst histograms of the clumps in tails, the dashed black lines are the age of the recent starburst histograms of the clumps in the disks, and the solid blue lines are the recent starburst histograms of the clumps in the nucleus for clumps in the SB&T sample, normalized by the total number of clumps in the SB&T sample. The solid and dashed green lines are the age of the recent starburst histograms of the clumps in the nucleus and in the disks, respectively, for clumps in the NIS galaxies, normalized by the total number of clumps in the NIS galaxies.

Figure 9. Isophotal radius at 25 mag arcsec$^{-2}$ in the B-band, $R_{25}$, vs. the effective radius in the J-band from 2MASS, $R_{\text{eff}}$, for SB&T and NIS galaxies. The solid line is the linear fit to the data points, while the dashed line is the one-to-one relation.

Galaxies, color-coded with the PDF. We add to this plot the fit from the clumps in NIS (top panel) to compare how the SFR radial profile differs in both samples. We extrapolate the last value of Equation (7) for the last radial bin for the NIS galaxies to larger radii, to compare with the tidal features of the SB&T galaxies.

$\Sigma_{\text{SFR}}$ is on average larger in SB&T clumps compared to NIS clumps. To study in more detail the differences between the SFR radial profiles in the SB&T and NIS galaxies samples, we derive $\Sigma_{\text{SFR,SB&T}}/\Sigma_{\text{SFR NIS,fit}}$, which is the ratio between the observed $\Sigma_{\text{SFR}}$ and that derived from Equation (7) and the extrapolation using the corresponding $R_{\text{gal}}/R_{25}$ value for the clumps in disks and tails from the SB&T galaxies. We plot $\Sigma_{\text{SFR,SB&T}}/\Sigma_{\text{SFR NIS,fit}}$ versus $R_{\text{gal}}/R_{25}$ in the bottom panel of
Figure 10, where we show how the SFR surface density increases toward the central parts of the SB&T galaxies compared to the NIS between $R_{\text{gal}}/R_{25} \sim 0.4$, which is in agreement with theoretical models of galaxy interactions, where gas inflows are produced by the loss of axisymmetry. There is less SFR enhancement toward inner regions $R_{\text{gal}}/R_{25} < 0.4$, except the nuclear regions, which present a median enhancement of 2.4.

In Figure 10 (bottom) we also show that the SFR surface density increases toward the external parts of the SB&T galaxies compared to the NIS between $R_{\text{gal}}/R_{25} \in [1, 6.5]$. We extrapolate the exponential fit derived (Equation (7)) to external regions using the value of the last radial bin from the NIS galaxies, since we do not observe clumps in the NIS galaxies beyond $R_{\text{gal}}/R_{25} \sim 2$. Although this extrapolation may not represent the real values, it is a conservative upper limit of $\Sigma_{\text{SFR}}$ for the clumps in NIS. The SFR enhancement in the external parts of galaxy mergers is highly debated because the evidence of the enhancement has been based on individual cases. Here, we present evidence for a larger sample of galaxy pairs in intermediate-early stages of interaction, where the SFR is clearly enhanced far from the nucleus. We obtain an SFR enhancement for clumps in the SB&T galaxies where $R_{\text{gal}}/R_{25} > 2$ of $\frac{\Sigma_{\text{SFR \, SB&T}}}{\Sigma_{\text{SFR \, NIS}}} > 2.1$.

6. Discussion and Conclusion

We present a stellar population synthesis analysis of 879 clumps from the SB&T galaxy sample, and 541 clumps from the NIS galaxy sample using the CIGALE SED modeling code, and UV, optical, and IR photometry of the clumps. Using CIGALE we obtained the SFRs, stellar masses, ages of the most recent burst, and fractions of the most recent burst, for the identified clumps.

The resolved star formation main sequence was presented by Cano-Díaz et al. (2016), Maragkoudakis et al. (2017), and Abdurro’uf & Masayuki (2017) for nearby galaxies, where they showed that it does hold on kiloparsec scales ($1–2$ kpc). However, we find that for the identified clumps at 1 kpc scales, the main sequence begins to breakdown in the NIS galaxies, and more intensely in the SB&T galaxies, while for the clumps at 2.5 kpc scales the main sequence holds, although it presents a higher scatter compared to that of the integrated star formation main sequence for NIS galaxies. We selected those...
scales in an effort to study star formation in higher resolution (1 kpc) due to the proximity of the sources to us (those with $D < 67$ Mpc), and also to study star formation for all the galaxies. We were limited by the most distant galaxy, Arp 107, at 142 Mpc, and the resolution of the GALEX and Spitzer 24 µm images, which approximately corresponds to 2.5 kpc at 142 Mpc. We show that the resolved star formation main sequence breaks down at small scales (between 1 and 2.5 kpc). As in the case of the Kennicutt–Schmidt law, which breaks down for sub-kpc scales (Bigiel et al. 2008; Onodera et al. 2010), a break is expected a small scales since stellar mass and star formation rate trace different properties of the star formation process, and these breaks could be used to constrain unknown quantities related to the star formation such as the duration of different star formation phases (Kruisjes & Longmore 2014).

The breakdown is more notable in the clumps from the SB&T galaxies, where the SFR is higher per stellar mass compared to the clumps in NIS galaxies. The SFR excess in the SB&T galaxies is probably triggered from the interactions, since they drive gas flows, increase turbulence, and compress gas. Therefore, at least in the nearby universe, the SFR surface density and the stellar mass surface density relation was affected by the environment, where galaxy pairs present higher SFR excess. Mergers should not be important drivers of the SFR enhancement observed at higher redshifts (Madau & Dickinson 2014), because the star formation main sequence has been observed to be tight even at high redshifts (Rodighiero et al. 2011; Speagle et al. 2014). Thus, higher gas fractions have been proposed as a mechanism to enhance SFR at higher redshift, and when mergers occur the SFR is already saturated (Fensch et al. 2017).

We show that the scatter of the integrated star formation main sequence is larger for SB&T galaxies compared to NIS galaxies. However, the star formation main sequence evolves with redshift, so the discrimination between the main sequence and the starburst regime could also evolve. Whether or not mergers drive higher star formation at earlier epochs, the clumps presented here have an excess in their SFR due to higher gas fractions enhanced by gas inflows due to the interaction, and are thus excellent laboratories to test models of star formation; see, e.g., Elmegreen (1997), Silk (1997), Bournaud et al. (2007), Zamora-Avilés et al. (2012), Zamora-Avilés & Vázquez-Semadeni (2014), and Krumholz et al. (2017), especially in an enhanced regime such as the clumpy star formation observed at higher redshifts (Elmegreen et al. 2009; Förster Schreiber et al. 2011; Guo et al. 2015).

Evidence in favor of a deviation from the KS law of star formation is the extended SFR excess reported here in the external parts of the SB&T galaxies in comparison with the clumps in NIS. Galaxy simulations assuming only a KS law of star formation are unable to predict the extended SFR excess in galaxy collisions (Moreno et al. 2015). The classical picture of gas inflows toward the central parts of merging galaxies is not enough to explain the extended enhanced star formation. Collisionally driven waves (Struck 1999), tidal tails (Duc & Renaud 2013), and shock-induced star formation (Barnes 2004; Chien & Barnes 2010) have been proposed as mechanisms to induce extended star formation in galaxy collisions. Also, Bournaud (2011), Powell et al. (2013), and Renaud et al. (2014) presented simulations with enough resolution to capture the turbulence of the cold gas, which predict deviations from the KS law of star formation, showing that compressive modes of turbulence are enhanced in galaxy mergers and produce extended star formation, as we observe in the SB&T galaxies, and in agreement with the velocity dispersion enhancement in interacting galaxies reported by Zaragoza-Cardiel et al. (2015).

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**Software:** CIGALE (Noll et al. 2009), Astropy (Astropy Collaboration et al. 2013), APLpy (Robitaille & Bressert 2012).

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