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High-resolution Hubble Space Telescope Imaging Survey of Local Star-forming Galaxies. I. Spatially Resolved Obscured Star Formation with H\(\alpha\) and Paschen-\(\beta\) Recombination Lines

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Abstract

We present a sample of 24 local star-forming galaxies observed with broadband and narrowband photometry from the Hubble Space Telescope (HST) that are part of the Great Observatories All-sky Luminous Infrared Galaxies Survey of local luminous and ultraluminous infrared galaxies. With narrowband filters around the emission lines H\(\alpha\) (and [N \(\text{II}\)]) and Pa\(\beta\), we obtain robust estimates of the dust attenuation affecting the gas in each galaxy, probing higher attenuation than can be traced by the optical Balmer decrement H\(\alpha\)/H\(\beta\) alone by a factor of >1 mag. We also infer the dust attenuation toward the stars via a spatially resolved spectral energy distribution fitting procedure that uses all available HST imaging filters. We use various indicators to obtain the star formation rate (SFR) per spatial bin and find that Pa\(\beta\) traces star-forming regions where the H\(\alpha\) and the optical stellar continuum are heavily obscured. The dust-corrected Pa\(\beta\) SFR recovers the 24 \(\mu\)m inferred SFR with a ratio of −0.14 ± 0.32 dex and the SFR inferred from the 8 to 1000 \(\mu\)m infrared luminosity at −0.04 ± 0.23 dex. Both in a spatially resolved and integrated sense, rest-frame near-infrared recombinations lines can paint a more comprehensive picture of star formation across cosmic time, particularly with upcoming JWST observations of Paschen-series line emission in galaxies as early as the epoch of reionization.

Unified Astronomy Thesaurus concepts: Extragalactic astronomy (506); Interstellar medium (847); Star formation (1569); Interstellar dust extinction (837); Luminous infrared galaxies (946)

1. Introduction

Past and recent multiwavelength extragalactic surveys both on the ground and in space (e.g., Cosmic Evolution Survey, Laigle et al. 2016; Weaver et al. 2022; Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey 3D-HST, Grogin et al. 2011; Koekemoer et al. 2011; Skelton et al. 2014; UltraVISTA, McCracken et al. 2012; Muzzin et al. 2013; UKIRT Infrared Deep Sky Survey, Lawrence et al. 2007; Hubble Frontier Fields, e.g., Shpley et al. 2018), have allowed us to closer examine the evolutionary processes in many thousands of stellar-mass-selected galaxies back to when the universe was only 1.5 Gyr old. Well-sampled photometry of these objects enables us to robustly model their spectral energy distributions (SEDs) and thus estimate their redshifts and study the properties of their stellar populations (e.g., stellar mass, star formation rate/history, dust attenuation) over a wide range of redshifts. We can then study how these galaxies form, evolve, and interact across the cosmic time. However, the SED fitting approach relies on a number of assumptions (e.g., the initial mass function, dust geometry and extinction law, star formation history; see, e.g., Conroy 2013 for a review), which are often overly simplified and surprisingly poorly constrained, even in the nearby universe.

To derive the intrinsic properties of a galaxy, one must have an in-depth understanding of the dust content of the sources, as it modifies the galaxies’ inherent SEDs in a wavelength-dependent way, in terms of both extinction and reddening. The dust in a galaxy absorbs the stellar emission in the UV and reemits it at longer wavelengths. A commonly used dust obscuration prescription is the local starburst attenuation curve (e.g., Calzetti et al. 2000). For normal star-forming galaxies, a Milky Way–like or Magellanic Clouds attenuation curve may be more appropriate (e.g., Kriek & Conroy 2013). Therefore, even in the local universe the attenuation curve is not universal (Calzetti et al. 2000). As we look back in time, the conditions we observe and measure in galaxies change (star formation rate, metallicity, dust content, etc.), and it remains unknown whether these attenuation curves are valid for high-redshift galaxies or the variations in these properties make them also dependent on redshift (see, e.g., Roebuck et al. 2019; Salim & Narayanan 2020).

Hydrogen recombination lines can be used to derive both the dust extinction and geometry. The most common pair of recombination lines used for this purpose is the Balmer decrement, H\(\alpha\)/H\(\beta\). However, recent works find that the classic
Balmer decrement underestimates the attenuation in galaxies when compared to the Balmer-to-Paschen decrement \( (\text{H} \alpha / \text{Pa} \beta) \). For instance, Liu et al. (2013; hereafter L13) show that the ratios between redder lines (e.g., \( \text{H} \alpha / \text{Pa} \beta \)) can probe larger optical depths than bluer lines such as the Balmer decrement by \( >1 \text{ mag} \). Calzetti et al. (1996) find equivalent results with the \( \text{Pa} \beta / \text{Br} \gamma \) ratio on a sample of local starburst galaxies. The Balmer-to-Paschen decrement \( (\text{H} \alpha / \text{Pa} \beta) \) technique has been demonstrated for Local Group H II regions (Pang et al. 2011; De Marchi & Panagia 2014), for a portion of the nearby starburst M83 (L13), and more recently employed at somewhat higher redshifts (Cleri et al. 2022). However, to date this technique has not been used extensively for systematic study of the extinction properties of local galaxies, nor with the quality and high spatial resolution of the Hubble Space Telescope (HST). Local Seyfert, luminous and ultraluminous infrared galaxies often have significant attenuation with \( A_V > 2 \text{ mag} \) over a large fraction of the visible extent of the galaxies (e.g., Kreckel et al. 2013; Mingozzi et al. 2019; Perna et al. 2019, 2020); all abovementioned arguments suggest that even larger attenuations might be present in these classes of sources.

The strength of using hydrogen recombination lines to infer dust obscuration lies in the fact that the intrinsic line ratios show relatively little variation across a broad range of physical conditions of the ionized gas. As shown in L13, assuming Case B recombination, with changes in the temperature between \( 5 \times 10^3 \text{ and } 10^4 \text{ K} \), and in the electron density of an H II region between \( 10^2 \text{ and } 10^3 \text{ cm}^{-3} \), the \( \text{H} \alpha / \text{Pa} \beta \) line ratio only changes between 16.5 and 17.6 (\( \sim 7\% \), Osterbrock 1989). For the analysis below, we adopt an electron density \( n_e = 10^3 \text{ cm}^{-3} \) and temperature \( T_e = 7500 \text{ K} \) as in, e.g., L13 for M83), resulting in an intrinsic ratio \( (\text{H} \alpha / \text{Pa} \beta)_{\text{int}} = 17.56 \) (Osterbrock 1989). Under the assumption of constant electron density and temperature, deviations measured from this intrinsic value can thus be directly associated to dust attenuation.

Near-infrared Paschen-series lines (e.g., \( \text{Pa} \alpha \) and \( \text{Pa} \beta \) at wavelengths 1.876 and 1.282 \( \mu \text{m} \), respectively) have been used to reveal star formation activity that is otherwise obscured for visible hydrogen recombination lines such as \( \text{H} \alpha \) and \( \text{H} \beta \), as well as for the optical emission from the stellar continuum (e.g., Tateuchi et al. 2015; Piqueras-López et al. 2016; Larson et al. 2020; Cleri et al. 2022). They have also been compared to IR-based SFR indicators (e.g., \( L(8–1000 \mu \text{m}) \); Kennicutt 1998), to check whether one can recover the star formation activity after applying dust corrections. Other studies directly suggest that one cannot use rest-optical lines to estimate physical properties of entire starburst systems, and one should instead aim to obtain rest-frame near-IR observations (Puglisi et al. 2017; Calabrò et al. 2018). Other recent works have used radio emission (specifically free–free emission) to measure star formation, in addition to IR and recombination lines (e.g., Murphy et al. 2018; Linden et al. 2019, 2021; Song et al. 2021). Free–free emission does not have the caveat of being affected by extinction as is the case for recombination lines. However, no study has had both the high quality and spatial resolution that HST can offer. This work opens an exciting avenue in spatially resolved studies that will become increasingly available with upcoming JWST observations.

Recent works show a larger amount of dust obscuration with increasing redshift among the most massive galaxies \( \log (M / M_\odot) > 10.5 \); Brammer et al. 2009; Marchesini et al. 2014; Skelton et al. 2014; Marsan et al. 2022). The detection of many of these objects in the Multiband Infrared Photometer for Spitzer (MIPS) 24 \( \mu \text{m} \) band implies that they have \( L_\text{IR} > 10^{11} L_\odot \), typical of luminous and ultraluminous infrared galaxies (LIRGs and ULIRGs; Sanders & Mirabel 1996). At \( z < 1 \), this population of galaxies seems to have generally diminished (Marchesini et al. 2014; Hill et al. 2017). The major complication to comprehend these systems is that at high redshift they might be multiple unresolved objects in the process of merging (Decarli et al. 2017; Silva et al. 2018; Marsan et al. 2019; Jones et al. 2020; Bischetti et al. 2021), as well as how little we know about the dust distribution in them, leading to oversimplified assumptions of their dust modeling.

Understanding the dust distribution in local LIRGs and ULIRGs is imperative for furthering our comprehension of the population of massive galaxies at the peak of star formation \( (z \sim 2; \text{Madau} & \text{Dickinson} 2014) \). Beyond \( z > 1 \), U/LIRGs begin to play an important part in the evolution of the star formation history of the universe, increasing its contribution with redshift, to the point of even dominating the SFR activity at \( z \sim 2 \) (e.g., Pérez-González et al. 2005; Magnelli et al. 2013; Zavala et al. 2021). These LIRG studies show that obscured star formation contributes the most to the SFR density. Instruments such as the Wide Field Camera (WFC) 3 onboard the HST allow us to closely examine this by obtaining the \( \text{H} \alpha \) and \( \text{Pa} \beta \) extinction maps and star formation estimates. Although separated by billions of years of evolution, local highly luminous objects appear similar to very distant massive dusty galaxies, in terms of for example their high infrared luminosity, large amounts of dust obscuration, \( \text{H} \alpha \) size, and surface brightness (see, e.g., Arribas et al. 2012). Therefore, by exploiting the high spatial resolution and high signal-to-noise ratio \( (S/N) \) of these local systems, we can at the same time aid our closer examination of the distant universe. On the other hand, these local objects appear to be different to higher redshift systems in terms of the distribution of the star formation and the dust temperature (Muzzin et al. 2010; Belloccchi et al. 2022). Furthermore, high-redshift U/LIRGs are more extended and display a cooler IR SED (Elbaz et al. 2011).

In this paper we present the observations and first results of a multiwavelength study of 24 nearby galaxies \( (z < 0.035) \) observed with the HST, to study the spatially resolved properties of their dust-obscured stellar populations and star formation activity. Using data from our own recent program along with archival observations, we obtain, at a minimum, narrow-band images centered on the redshifted \( \text{H} \alpha \) and \( \text{Pa} \beta \) recombination lines and corresponding optical and near-infrared broadband continuum images in filters similar to the rest-frame \( I \) and \( J \) bands. Archival observations of a subset of the full sample provide additional broadband images extending the SED sampling to the near-ultraviolet wavelengths. We develop a spatial binning procedure with Voronoi tessellation that probes spatial scales as small as 40 pc at the median redshift of our sample \( (z = 0.02) \), and an SED fitting technique that robustly infers emission-line fluxes from the narrowband images.

This paper is structured as follows. In Section 2, we introduce the HST observations and data processing procedure. Section 3 describes the methodology we develop for the spatially resolved image analysis, including spatial binning and multiband SED fitting software. In Section 4, we present the main results and properties of our sample, as well as discussing the implications of our findings. Finally, Section 5 presents a
summary of our work and corresponding conclusions. Throughout this paper, we assume a Chabrier (2003) initial mass function (IMF) and a simplified ΛCDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$. We use the biweight location and scale statistics defined by Beers et al. (1990), when referring to derived mean values and their uncertainties.

2. Data and Observations

We conducted an HST snapshot survey program in Cycle 23 (HST-14095, Pf: Gabriel Brammer; Brammer 2015) to obtain narrowband images of nearby galaxies centered on the (redshifted) He$\alpha$ and Pa$\beta$ hydrogen recombination lines. The full target list of the survey was defined as essentially any nearby galaxy ($z < 0.05$) that had existing wide-field HST archival imaging in either narrowband He$\alpha$ from ACS/WFC or WFC3/UVIS, or Pa$\beta$ from WFC3/IR, to which we added the missing narrow band and an associated broadband continuum filter. The combination of the parent selection and the fact that a random subset of them were observed as snapshots, yields a heterogeneous sample in terms of the star formation rate, stellar mass, morphology, etc. ($0.01 < \text{SFR} [M_{\odot} \text{ yr}^{-1}] < 200$; $10^{\text{.7} - 2} < M_\star [M_{\odot}] < 10^{1.55}$; and in terms of the morphology, from spirals to irregulars and mergers). The observations are available for a sample of 53 galaxies, 24 of which are in the Great Observatories All-sky Luminous Infrared Galaxies Survey (GOALS) of local luminous and ultraluminous infrared galaxies ($z < 0.088$, $L_{\text{IR}} > 10^{11}L_{\odot}$; Armus et al. 2009).

The number of available imaging filters from the ultraviolet through the near-infrared varies significantly across the full sample. At the very least, each target has narrowband images from WFC3/UVIS, ACS/WFC, or WFC3/IR.

Notes. The infrared luminosity is from GOALS (normalized to our cosmological parameters using Wright 2006). The redshift is from Chu et al. (2017). The filters added by the Cycle 23 SNAP program (HST-14095, Brammer 2015) are indicated with lower-case letters, whereas the rest are archival data.

a Targets that host an AGN, X-ray-selected based on Iwasawa et al. (2011), Torres-Albà et al. (2018), or Ricci et al. (2021).

b Targets that do not host an AGN, based on Iwasawa et al. (2011), Torres-Albà et al. (2018), or Ricci et al. (2021).
Each image was processed created using the Drizzle Pac (Gonzaga et al. 2012) modules TweakReg for relative alignment and AstroDrizzle for image combination and stacking. The original pixel size of the images obtained with the WFC3/IR channel is 0.128 pixel$^{-1}$. The images are drizzled to combined mosaics with 0.1 pixel$^{-1}$ for the IR filters and 0.05 pixel$^{-1}$ for the optical ACS/WFC and WFC3/UVIS filters.9 Our sample spans redshifts from 0.0001 to 0.035, with a median $z \sim 0.02$. This corresponds to a physical size of 0.3–70 pc pixel$^{-1}$, $\sim 40$ pc pixel$^{-1}$ at the median redshift (for the 0.1 WFC3/IR pixels).

Our galaxies span a wide range in infrared luminosity ($8.9 < \log(L_{IR}/L_{\odot}) < 12.3$), as can be seen in Figure 1, which yields a very heterogeneous sample, also in terms of, e.g., stellar mass and morphology. A large number of our galaxies are undergoing starbursts (as we would expect for the GOALS sample selection criteria, which are all above the main sequence in Figure 1), most likely driven by mergers in some cases, as we can see paired galaxies in our HST images. In the work presented in this first paper, where we focus on the study of the star formation activity inferred with different tracers, we only use the targets from the GOALS sample in our analysis (Table 1), due to the availability of measurements for their infrared luminosities and 24 μm fluxes. We present additional galaxies in the Appendix (Table 3), for which we have processed the HST data as explained above, but that are not part of the analysis in this work. These targets often have spatial extent larger than the field of view (FOV) of the instrument.

9 All of the aligned image mosaics are available at http://cosmos.phy.tufts.edu/dustycosmos/.

3. Methodology

In this work we develop two main methodologies to first derive spatial bins that homogenize the measurement signal-to-noise across the extent of each target galaxy, and second to analyze the (binned) multiband SEDs, that include measurements from as many as 12 broadband and narrowband imaging filters from NUV to NIR wavelengths.

3.1. Voronoi Binning

Modern instruments allow us to spatially resolve nearby extended sources, although these observations can display a significant anisotropy in the signal-to-noise ratio (S/N) across the target. Sometimes these variations differ by orders of magnitude, and some pixels often have poor S/N. To resolve this, the spatial elements can be grouped locally (binned) to obtain a more uniform S/N across the image; however this results in a loss of spatial resolution.

Disk galaxies typically have “exponential” surface brightness profiles (Boroson 1981); thus the outskirts are much fainter than the centers. With this in mind, we implement an adaptive binning scheme; for lower S/N, larger bins are created, whereas for high-S/N regions, the bins are smaller and a high resolution is maintained. For this, we adapt the Voronoi binning procedure from Cappellari & Copin (2003). This method implements adaptive spatial binning of integral-field spectroscopic data to achieve a specified constant S/N per spatial bin.

The Cappellari & Copin (2003) Voronoi algorithm10 is inefficient for handling data sets with millions of data points as is the case for the large image mosaics used here. Furthermore, the algorithm is not robust in the regime of low S/N per original data point (Cappellari & Copin 2003), as in the outskirts of the galaxies in our HST images. Therefore, we adopt a hybrid approach of block averaging the galaxy mosaics in progressively shrinking box sizes and applying the Voronoi algorithm on the blocked image. A detailed explanation of our binning procedure11 is provided in Appendix A.

For the spatial binning, we set a target S/N ratio of at least 20 per bin in the narrowband image that includes Paβ, to ensure a minimum constant S/N across the resulting Paβ emission-line image once the continuum is subtracted, where the per-pixel uncertainties are provided by the HST imaging calibration pipelines (e.g., Section 3.3.5 of the WFC3 Data Handbook; Sahu 2021). The spatial bins derived from the Paβ narrowband image are then applied to all other available filters for a given target, so that we can measure photometry for each spatial bin across the filters. The threshold S/N imposed on the Paβ narrowband image is not necessarily achieved in all the other filters (e.g., UV filters, where S/N can be low), whereas it can also be higher in broadband filters such as F110W. Rather than matching the wavelength-dependent point-spread functions (PSFs) of the different filters, which involves a convolution with an imperfect matching kernel and modifies the pixel variances in a nontrivial way, we adopt a minimum bin size of $2 \times 2$ 0.1 pixels so that the bins are larger than the PSF FWHM of any of the individual images. Figure 2 shows a demonstration of the binning scheme for targets MCG-02-01-051 (top panels) and NGC 1614 (bottom panels).

10 https://www.astro.physics.ox.ac.uk/~mxc/software/
11 https://github.com/claragimenez/voronoi
3.2. Continuum Subtraction

The raw flux density measured in a narrowband filter centered on an emission line includes contributions from both the line itself and any underlying continuum, where the fractional contribution of the continuum increases with the width of the filter bandpass. To produce pure hydrogen emission-line images (Hα and Paβ line fluxes in our case), we first need to remove the contribution from the stellar continuum. A common approach to deal with this issue is to perform a “simple” background subtraction, in which a nearby broadband filter (or an interpolation of multiple broadband filters) is scaled and subtracted from the respective narrowband filter containing the emission line of interest using some estimate of the continuum shape across the various bandpasses. A linear continuum shape is generally either assumed explicitly or implicitly (e.g., a flat spectrum that defines the photometric calibration of the various filters) or estimated empirically from the color of a pair of continuum filters bracketing the narrow line bandpass (as is done in, e.g., Liu et al. 2013; Calzetti et al. 2021). The adopted broadband or medium-band continuum filters may or may not contain the line of interest. A narrowband filter adjacent to the narrowband line filter can provide a relatively robust continuum estimate, though it is relatively more expensive to reach a given continuum sensitivity as the bandpass shrinks. In all of the cases above, the continuum shape is likely the dominant source of systematic uncertainty on deriving the emission-line flux from the narrowband image.

In this work we develop a new approach to derive the continuum and emission-line contributions that uses all of the available information by fitting population synthesis templates to the spatially resolved photometry in all available filters for a given target. It is inspired by the photometric redshift fitting code EAZY (Brammer et al. 2008), with the motivation to precisely fit the contribution from the stellar continuum and the lines separately, in order to produce robust line fluxes without stellar continuum contamination. Our code fits a set of continuum and line emission templates on a bin-to-bin basis, in order to infer spatially resolved physical properties of our nearby galaxies. In the next section, as well as in Appendix B, we explain our SED fitting code in further detail.

Figure 3 shows an example of the HST coverage that we can have for one of our targets. We have two narrowband filters targeting Hα (purple coloring) and Paβ (orange coloring), as well as broadband neighboring filters, F814W and F110W in this case. A flat sloped spectrum (turquoise dashed line) and a redshifted galaxy SED (black line) are plotted and could be used in “simple” continuum subtraction methods to remove the stellar continuum emission from the narrowband filters. As we can see, the F110W broadband filter contains the emission line, and would lead to oversubtraction if used for this purpose. On the other hand, we could have off-band narrowband filter coverage, such as F130N in Figure 3, which would allow an analytical solution to subtract the continuum (in this case, iterative subtraction methods are used), but this is not always available, therefore justifying our need to develop a novel methodology. Sections 3.4.1 and 3.4.2 display comparisons between different subtraction methods in further detail.

3.3. SED Fitting

As introduced in the previous section, we develop an SED fitting code to accurately fit the continuum and line emissions in order to obtain the Hα and Paβ line fluxes. Furthermore, our method allows us to derive spatially resolved physical properties, fitting each galaxy on a bin-to-bin basis, obtaining local estimates such as the star formation rate (SFR) and stellar mass.

We develop an adaptation of the Python-based version of EAZY12 (Brammer et al. 2008), which we make publicly available.13 Like EAZY, our code finds the linear combination of templates that best fits all of the observed photometry of each spatial bin. We use a set of four continuum templates and two extra line templates, one with Hα+[N II] in a fixed ratio of 0.55, (see Section 3.4.1 below) and the other with Paβ emission, that allow us to fit the emission lines separately.14 Analogous to the stepwise SFH parameterization of the Prospector-α software (Leja et al. 2017; Johnson & Leja 2017), we choose four continuum templates to reasonably sample the star formation histories, but without adding excessive flexibility that would lead to the SFHs not being properly constrained by the limited data that we have. The continuum templates are generated with Python flexible stellar population synthesis (FSPS; Conroy et al. 2009; Conroy & Gunn 2010; Johnson et al. 2021), that allows us to specify our own SFHs, for stepwise time bins between 0, 50, 200, 530 Myr, 1.4 Gyr with constant SFR across each bin (see Section B). However, by deriving the template scaling coefficients using standard least-squares optimization we do not impose any priors on the relative contributions of the stepwise SFH bins. The template normalization coefficients are transformed to emission-line fluxes and star formation rates and stellar masses of the continuum-emitting stellar population, and the analytic covariance of the fit coefficients is used to compute the posterior distributions of those derived parameters. This fitting approach is dramatically faster than sampling codes such as Prospector—running ∼800 spatial bins of a single target galaxy with Prospector requires 1–2 weeks on a supercomputer on average, whereas we can perform the full fit in the same galaxy in under 5 minutes with our code and a fairly standard laptop computer.15 In Appendix B we discuss additional considerations of the choice of templates and the SED fitting code.

A new implementation with respect to the EAZY machinery is the addition of a reddening grid. Instead of fitting for redshift, which is well-known for the nearby galaxies in our sample, we construct a reddening grid where we redden the continuum templates by a given amount, and fit the normalization coefficients of the two emission lines and reddened continuum templates. The attenuation curve used to redden the continuum templates can be input by the user. In this work we use a Calzetti et al. (2000) attenuation curve. The introduction of the line templates to directly fit the line fluxes is the main novelty and motivation behind developing our spatially resolved SED fitting code. This allows us to constrain on the one hand the attenuation traced by the stellar continuum, which is due to the diffuse interstellar medium (ISM), and on the other hand, we are able to evaluate the attenuation that the gas suffers, traced by the inferred empirical decrement Hα/Paβ.3

As discussed in, e.g., Greener et al. (2020), the “extra” attenuation experienced by the gas is due to stellar birth clouds, which are

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12 https://github.com/gbrammer/eazy-py
13 https://github.com/claramigenez/SED_fit_photometry
14 We do not fit for additional near-infrared emission lines (e.g., [S III] λλ9070,9530, He 1 λ10830) that can contribute up to ∼12% of the signal in the broad F110W filter.
15 Tested on a 2 GHz Quad-Core i5 CPU.
H II regions enshrouded in dust, where dust is clumpier than in the diffuse ISM, and it can be traced with nebular emission lines (Hα and Paβ in our study).

Our SED fitting code finds the best-fit solution by minimizing χ², defined as in Brammer et al. (2008):

\[ \chi^2_{\lambda V} = \sum_{j=1}^{N_{\text{fit}}} \frac{(T_{\lambda V,j} - F_j)^2}{(\delta F_j)^2}, \]

where \( N_{\text{fit}} \) is the number of filters, \( T_{\lambda V,j} \) is the synthetic flux of the linear combination of templates in filter \( j \) for reddening \( A_V \), \( F_j \) is the observed flux in filter \( j \), and \( \delta F_j \) is the uncertainty in \( F_j \), obtained combining the observed uncertainty and the template error function (see Brammer et al. 2008 for more information). Once we find our best-fit linear combination, we directly infer the line fluxes Hα and Paβ from the fitted line emission templates. We do this on a bin-to-bin basis, and the ensemble result is the spatially resolved fit across the face of the target galaxy. Our SED fitting code allows user input for a variety of parameters and files, such as the templates that are used to fit both the continuum and the lines, making the code flexible to fit both contributions across all wavelength ranges, as long as the input templates cover the desired interval and line emissions.

In summary, our SED fitting procedure outputs the line fluxes Hα and Paβ in erg s⁻¹ cm⁻², as well as various physical properties: the extinction \( A_V \) obtained from the “empirical” Balmer-to-Paschen decrement (\( A_V(H\alpha/\text{Pa}\beta) \)) and the \( A_V \) inferred from the stellar population (\( A_V \) or \( A_V(\text{continuum}) \) derived with the continuum templates). We also obtain the SFR and stellar mass \( (M_*) \) (surface density) in each spatial bin.

Additionally, while the SFR from the SED fit estimates the star formation activity throughout the last ∼100 Myr, we derive the instantaneous (∼10 Myr) SFR from the Hα luminosity, following the Kennicutt (1998) relation, and dividing by 1.8 (Calzetti et al. 2007; Kennicutt et al. 2009) to convert from a Salpeter (1955) IMF to Chabrier (2003):

\[ \text{SFR}[M_\odot\text{yr}^{-1}] = 4.4 \times 10^{-42}L_{\text{H}\alpha,\text{corr}} [\text{erg s}^{-1}], \]

where \( L_{\text{H}\alpha,\text{corr}} \) is the dust-corrected Hα luminosity, calculated as:

\[ L_{\text{H}\alpha,\text{corr}} = L_{\text{H}\alpha,\text{obs}} \times 10^{0.4A_{\lambda}}, \]

where \( A_{\lambda} \) is the extinction at the Hα wavelength and can be obtained using the parameterization of the attenuation \( A_\lambda = k(\lambda)E(B-V) \), where \( k(\lambda) \) is given by an attenuation curve, which we must assume, and \( E(B-V) \) is the color excess, which we can calculate in terms of the Paschen-β and Hα.
observed ratio (e.g., Calzetti et al. 1996):

$$E(B - V) = \frac{2.5}{k(\text{Pa}3) - k(\text{H}\alpha)} \log \left( \frac{\text{H}\alpha / \text{Pa}3_{\text{obs}}}{\text{H}\alpha / \text{Pa}3_{\text{int}}} \right),$$  \hspace{1cm} (4)

where \(\text{H}\alpha / \text{Pa}3_{\text{int}}\) is the intrinsic ratio (that we set to be 17.56, as explained before). Following Calzetti et al. (2000) and subsequent work, the emission lines follow the standard Milky Way curve (Fitzpatrick 1999), so \(k(\text{Pa}3) = 0.76\) and \(k(\text{H}\alpha) = 2.36\). Equivalently, we can infer the most recent SFR with the Pa3 emission instead, which later on is analyzed in depth and compared with other star formation tracers in Section 4. The SFR inferred with the Pa3 luminosity is given by:

$$\text{SFR}[M_{\odot} \text{yr}^{-1}] = 4.4 \times 10^{-42} \times \frac{\text{H}\alpha}{\text{Pa}3_{\text{int}}} \times L_{\text{Pa3,corr}} \left[ \text{erg s}^{-1} \right],$$  \hspace{1cm} (5)

where, equivalently to Equation (3), the dust-corrected Pa3 luminosity can be obtained with \(A_{\text{Pa3}} = k(\text{Pa}3) \times E(B - V)\), and we can use Equation (4) to obtain the color excess.

Finally, we can also infer the visual attenuation \(A_V = R_V E(B - V)\), obtaining \(E(B - V)\) from the line ratio as before. The Balmer-to-Paschen ratio only provides the actual value of \(E(B - V)\)—and therefore \(A_V\)—if the dust is distributed homogeneously and as a foreground screen, and the attenuation curve employed is appropriate for the case. Following Calzetti et al. (1994, 2000), we set \(R_V = 4.05\) for the stellar continuum and \(R_V = 3.1\) for the nebular lines.

Figure 4 shows an example of the results our spatially resolved SED fitting code produces for each individual bin in a galaxy. The code is run on NGC 1614, and it produces a best-fit SED (black line), shown in the upper right plot for one example bin toward the bulk of the galaxy. We show the original HST available photometry (red points and error bars) as well as the best-fit synthetic photometry (blue crosses). The choice of continuum and line templates that linearly combine to produce the best-fit SEDs are also displayed in different color curves. The bottom panel shows the residual \(\chi^2\) of the fit (data—model). On the left of Figure 4, we display the corner plot\(^{16}\) with the parameter space for the selected example bin. We can explore the different correlations between the various physical parameters, as well as seeing the distribution of best-fit solutions for each of them. This constitutes an upgrade in the treatment of correlations between parameters and resulting uncertainties in the physical properties that we infer, when compared to previous fast-running codes, and with the advantage of computational speed when compared to other Markov Chain Monte Carlo routines in other codes.

3.4. Robustness of Our Inferred Parameters

We can conduct some tests and diagnostics to analyze the robustness of the inferred physical properties, estimated with our spatially resolved SED fitting scheme. For this, we can use archival observations obtained with different instruments, as well as other SED fitting codes.

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\(^{16}\) We use the visualization Python package **corner.py** (Foreman-Mackey 2016)

First, we test how reliable our line fluxes are, which is vital if we want robust and trustworthy \(A_V(\text{H}\alpha / \text{Pa}3)\), SFR\text{H}\alpha, and SFR\text{Pa3} estimates. The narrowband filter that targets \(\text{H}\alpha(\lambda 6564.61 \text{Å})\) is wide enough so that we get contamination from the [NII]\(\lambda\lambda 6549.86,6585.27 \text{Å}\) doublet, so we need to correct for this. A common approach is to consider a fixed ratio throughout the galaxy; however, the [NII]/H\alpha ratio can vary significantly not only between galaxies, but also spatially within a galaxy (e.g., Kennicutt et al. 2007; Wuyts et al. 2013; Belfiore et al. 2016, 2017). Multiple processes can be responsible for these variations, e.g., ionization, shocks, outflows, differences in the electron density and metallicity, among others, (see, e.g., Kewley et al. 2019 for a review). It is common to use a correction of [NII]/H\alpha = 0.55 (e.g., Moustakas et al. 2010; Jin et al. 2019), which we also apply in this work, although the user can choose which correction to implement.

We also calculate and account for the corresponding contaminant factor of [NII], computed as the throughput of the narrowband filter of [NII] with respect to H\alpha.

Some of the galaxies in our sample have ground-based archival integral-field spectroscopy available (e.g., Very Large Telescope (VLT) Multi-Unit Spectroscopic Explorer (MUSE) for six objects from the GOALS sample), which can be used to measure the spatial variation of the [NII]/H\alpha line ratio, though at a somewhat lower spatial resolution than the HST maps. Here we use MUSE integral-field cubes of target MCG-02-01-051, to test the robustness of our method for inferring H\alpha emission-line fluxes from the multiband HST images.

We convolve the HST images with a Moffat kernel (Moffat 1969), to match the larger ground-based MUSE PSF (FWHM \(\sim 0.06\)) and resample them to the MUSE spatial pixel grid. We then recompute the Voronoi bins on the resampled HST images as described above in Section 3.1 and Appendix A, and apply the bins to the calibrated MUSE spectral cubes downloaded from the ESO archive. We fit for the fluxes of the H\alpha+[NII] emission lines in the resulting binned spectra with a triple Gaussian model, finding excellent agreement with our MUSE fits and previously published H\alpha maps on our targets (e.g., IRAS13120-5453 from the PUMA Project; Perna et al. 2021).

Figure 5 shows an example on target MCG-02-01-051, on the H\alpha+[NII] fit from MUSE compared to our HST SED fit H\alpha+[NII] estimate. The H\alpha fluxes derived with our fits to the HST broadband and narrowband photometry (left) agree remarkably well with the independent measurement from the MUSE spectral cube (right).

In Figure 6, we show a comparison of the resulting H\alpha emission inferred with the simple subtraction method, interpolating two continuum templates and subtracting from the narrow band that targets H\alpha (top panel), and the full SED fitting scheme (bottom panel) for galaxy MCG-02-01-051. We compare each of these with the direct H\alpha fit from the MUSE cube available for this target. The result clearly shows a greater discrepancy between the inferred H\alpha from the simple subtraction method and the MUSE fit (with a mean difference of \(-0.04 \pm 0.04 \text{ dex}\)), than the H\alpha from our SED fit method, which agrees considerably better with the MUSE measurement (with an improved mean discrepancy of only \(-0.02 \pm 0.04 \text{ dex}\)). Focusing on the bottom panel, we see that the large majority of the SED fit H\alpha fluxes agree well with the MUSE “ground truth”, with a larger scatter at a low HST flux that can be explained by...
the uncertainties. The slight tilt in the comparison likely arises from imperfections in the PSF and alignment matching between the MUSE and HST frames; if we perform the same analysis with the HST F673N (the narrow band that targets Hα) versus a synthetic F673N on MUSE (we integrate the MUSE spectra through the filter curve), we obtain the same trend, as well as if we perform the same test on the F814W filter, which does not contain the line.

Finally, we can check the $[\text{N II}]/\text{H}\alpha$ spatially resolved correction, inferred from the MUSE IFU cube. Figure 7 shows the spatial map and histogram of the derived ratio for MCG-02-01-051. We see that the ratio is not uniform across the face of the galaxy, but the constant value that we assume (0.55)—following the assumption that most studies make—falls within $1\sigma$ of the mean value for this galaxy. This value is reasonable for most H II-like galaxies and isolated LIRGs that comprise our sample, but we might encounter some targets that can have $[\text{N II}] > \text{H}\alpha$ across much of the extent of the galaxy, such as the extreme starburst Arp 220 (see Figure 14 in Perna et al. 2020) or galaxies with extended emission from a low-ionization nuclear emission-line region (LINER; e.g., Belfiore et al. 2015). Section C in the Appendix shows the resulting $[\text{N II}] / \text{H}\alpha$ histograms for the five additional targets from the GOALS.

We run this study for six targets that have MUSE cubes available and derive the same conclusions—that our $\text{H}\alpha + [\text{N II}]$ fluxes agree considerably well with the $\text{H}\alpha + [\text{N II}]$ emission measured directly from MUSE spectra, and we even see that our composite SED fit obtained with the different templates, fits the MUSE spectrum on a bin-to-bin basis, and not only the emission lines.
The running median and uncertainty are shown as a solid black line and surrounding shaded region, respectively. The running median matches the MUSE one better than the commonly used simple subtraction line estimates, and the reference MUSE H$\alpha$ shows the logarithm of the ratio between each HST subtraction method inferred SED machinery of the mean value we adopt for the ratio of the emission line.

Figure 6. Comparison of the resulting H$\alpha$ flux with a simple background subtraction method (top panel, interpolating two broadband filters) and our full SED machinery (bottom panel), on galaxy MCG-02-01-051. The vertical axis shows the logarithm of the ratio between each HST subtraction method inferred line estimates, and the reference MUSE H$\alpha$ of this source. The SED fit H$\alpha$ matches the MUSE one better than the commonly used simple subtraction method. The running median and uncertainty are shown as a solid black line and surrounding shaded region, respectively.

Figure 7. Histogram (top left inset plot) and spatial map (main plot) of the [N II]/H$\alpha$ ratio for MCG-02-01-051 as measured in the MUSE IFU cube. The value we adopt for the ratio (black dashed line on the histogram) falls within 1$\sigma$ of the mean (gray shaded region).

sample that have MUSE observations available. Naturally, where our assumed constant [N II]/H$\alpha$ value differs from the actual ratio, the inferred $A_V$ will be affected directly. For the extreme galaxy in our sample for which we have a MUSE cube, Arp 220, the mean [N II]/H$\alpha$ = 1.92 ratio observed in the cube corresponds in a systematic shift of 1.3 mag for $A_V$ relative to our assumed value of 0.55 (see Equation (C1)).

3.4.2. Paβ Emission-line Strength

While we do not have an IFU cube to test the Paβ line flux that we infer with our SED fitting code, we consider a subset of galaxies in our sample where a robust empirical subtraction can be performed with the paired narrowband images on and off of the emission line.

Figure 8. Comparison between the Paβ inferred from our SED fitting scheme and the scaled F130N off-band subtraction for each spatial bin. The running median and scatter are shown as a solid black line and surrounding shaded region, respectively.

Figure 8 shows the comparison between the Paβ line flux that we infer from our SED fit and the one obtained using the offset narrowband filter F130N. By scaling the F130N we can perform a simple empirical subtraction from the F132N measurement, and remove the stellar continuum from the narrow band that targets the recombination line. We see that our Paβ estimate for this galaxy agrees with the empirical simple method (with a mean difference of 0.03 ± 0.05 dex). There is a slight flux-dependent residual toward the bright end of the Paβ flux, where the discrepancy reaches ∼0.05 dex, which is still a good agreement overall.

This and the previous study allow us to show that our line fluxes are within 0.05 dex of their respective reference values, making them reliable and robust on a bin-to-bin basis. Furthermore, the resulting $A_{V,\text{gas}}$ inferred from the decrement and the SFRs inferred from both lines are also trustworthy.

3.4.3. Physical Properties from Prospector

To prove the robustness of first our $A_{V,\text{stars}}$ estimates, we use a different SED fitting code to fit our photometric observations, and compare the inferred $A_V$. For this, we use the SED fitting code Prospector\(^{17}\) (Leja et al. 2017; Johnson & Leja 2017). Both EAZY (and therefore our code) and Prospector incorporate FSPS (Conroy et al. 2009; Conroy & Gunn 2010) models, which are composite stellar population models that allow user input.

Until now, SED fitting techniques of galaxies have broadly adopted basic models to obtain stellar masses, with fixed stellar metallicities, simple parametric star formation histories (SFHs), rigid and simplistic dust attenuation curves, and minimization of chi-squared. On the other hand, Prospector includes a flexible attenuation curve and metallicity. Prospector uses FSPS, which contains nebular emission and considers both attenuation and reradiation from dust. It also provides some innovation on flexible SFHs, as well as techniques for sampling parameter distributions. It comprises a six-component non-parametric SFH. With such a wide and adjustable range of parameters, Prospector is able to supply realistic uncertainties and unbiased parameters.

We run Prospector on the target IRASF10038-3338 with both a parametric SFH and a nonparametric SFH. Both yield very similar results. Figure 9 (top left panel) shows the resulting $A_V$ maps inferred from Prospector with a non-parametric SFH (left) and with our SED fitting code (right).

\(^{17}\) https://github.com/bd-j/prospector
A priori, the maps seem to agree considerably well. Quantitatively (see the top right scatter plot in Figure 9), the mean difference between both AV estimates across the galaxy is 0.06 (≈6%), with a standard deviation of 0.25, reflecting on the good agreement between the two.

Furthermore, to do a sanity check on our SFR and stellar mass estimates (both inferred from the SED fitting and not the lines alone), we can compare them with the Prospector estimates for the same galaxy, IRASF10038-3338. With Prospector, we obtain the star formation rate density (SFRD) and stellar mass density (SMD), so to compare one to one, we simply divide our estimates by the corresponding physical bin size. At our average redshift of 0.02, for a minimum bin size of $4 \times 4$ pixels ($0.\!\!\!\!_{-0.4}^{+0.4}$ per side), this corresponds to 160 pc across, which results in a minimum bin area of $0.0256$ kpc$^2$.

Figure 9 shows the resulting qualitative and quantitative comparison between the two codes, using the nonparametric SFH for Prospector, although the parametric SFH run gives equivalent results. We see that both the SMD and SFRD maps (left middle and bottom panels of the figure, respectively) seem to agree considerably well on a bin-to-bin basis for this galaxy, especially the SMD, which our code samples particularly smooth, even in central bins where the Prospector fit seems to fail. Our code seems to infer a higher star-forming bulge than Prospector, most likely driven by the differences in SFH sampling from both codes and the SFH priors used. On a quantitative point of view (middle and bottom scatter plots of Figure 9), for the SMD, the mean discrepancy between the two estimates is $-0.07 \pm 0.08$ dex, which is a remarkable agreement. On the other hand, for the SFRD, we obtain a median difference between Prospector and our code of $0.15 \pm 0.19$ dex. We see that the largest difference is obtained at the bright end of the SFRD. Although this may seem like a large discrepancy, the SFR from SED modeling is one of the more uncertain stellar population properties to derive (see, e.g., Muzzin et al. 2009), and highly influenced in this comparison by the differences in SFH sampling. Broadly used SED fitting codes such as EAZY would yield equivalent results when compared to Prospector in terms of the SFRD.

To summarize, our inferred physical properties agree well both qualitatively and quantitatively (see Figure 9), which gives us confidence that our estimates are robust and trustworthy.

### 4. Results and Discussion

For all galaxies in our sample, we have produced Hα and Paβ maps, as well as extinction maps from the decrement and the stellar continuum, that allow us to measure the typical size scales and extinction levels of the dust obscuration. In this section we present the results. Maps of the various physical properties inferred with our SED fitting code can be found in Appendix E for each individual galaxy in our sample.

#### 4.1. Case Example

Before conducting a quantitative analysis on the various inferred line fluxes and physical properties, we present here a case example on our whole methodology applied to one target.
NGC 1614. As has been discussed in Section 3.1 (and Appendix A), the first step with our sample has been to employ a Voronoi tessellation binning scheme. Figure 2 showed the binning applied on NGC 1614 on the bottom panels. We apply the binning generated on F130N to the rest of available filters for this target, which are six images from the UV to the NIR.

Once we have the binned images, we apply our spatially resolved SED fitting code (see Section 3.3 and Appendix B), and obtain the resulting physical estimates that are shown in Figure 10. The top row, from left to right, shows the RGB image (built combining the F435W, F814W, and F110W broadband filters), the SMD map, and the SFRD maps inferred with the stellar continuum and with the Pa\(\beta\) emission-line flux. The bottom row shows the resulting H\(\alpha\) and Pa\(\beta\) surface density flux maps, as well as the \(A_V\) inferred from the empirical Balmer-to-Paschen decrement, and the stellar continuum. The top panel, blue points reveals obscured star formation that is invisible to optical lines, while the bottom panel, orange points shows the resulting H\(\alpha\) and Pa\(\beta\) surface density flux maps, as well as the \(A_V\) inferred from the empirical Balmer-to-Paschen decrement, and the stellar continuum. The differential attenuation inferred from each component will be addressed in detail in a forthcoming publication.

### 4.2. SFR Indicators

Accurately determining the star formation rate is a vital step in understanding galaxy evolution. There are numerous tracers of recent and past star-forming activity, and one can infer a comprehensive picture of the SFH and burstiness in galaxies by comparing different star formation rate indicators (Madau & Dickinson 2014).

In this section, we focus on exploiting our Paschen-line observations to trace the obscured star formation in our sample of nearby star-forming galaxies. First, we compare the optical and NIR SFRs inferred with H\(\alpha\), Pa\(\beta\), and the stellar continuum emission. Later on, we investigate whether the dust-corrected SFR inferred with Pa\(\beta\) can recover the SFR derived from the infrared luminosity and the 24 \(\mu\)m emission observed with MIPS/Spitzer. We conduct both spatially resolved and integrated comparisons for the various tracers. As mentioned before, we conduct this study only on the galaxies of our sample that are also part of GOALS, due to their \(L_{IR}\) and 24 \(\mu\)m flux measurements availability.

#### 4.2.1. Spatially Resolved Optical and NIR SFRs

As introduced before, we can infer the SFR over the last ~100 Myr from the stellar continuum emission. On the other hand, hydrogen recombination lines trace the most recent star formation (~10 Myr), occurring in H\(\Pi\) regions throughout the galaxy (Kennicutt & Evans 2012).

Using Equations (2) and (5), we can infer the SFR from the H\(\alpha\) and Pa\(\beta\) line fluxes, and divide by the physical size to obtain the star formation rate surface densities (in \(M_\odot\) yr\(^{-1}\) kpc\(^{-2}\)). Both SFRDs match once we apply the dust correction inferred from the H\(\alpha\)/Pa\(\beta\) decrement. On the other hand, for the targets where we have MUSE cubes available, we can correct for dust obscuration using the classic Balmer decrement (H\(\alpha\)/H\(\beta\)). This allows us to explore whether Pa\(\beta\) reveals obscured star formation that is invisible to optical lines, even after applying a dust correction.

Figure 11 shows the spatially resolved comparison between SFRD\(H_\alpha\) and SFRD\(Pa_\beta\) for galaxy MCG-02-01-051, without (top panel, blue points) and with (bottom panel, orange points) the dust-correction prescription applied, using the Balmer decrement obtained from the MUSE cube (indicated by the superscript “Balmer”). In both cases, the SFRD inferred with Pa\(\beta\) is systematically higher. There is a clear trend with the SFRD\(Pa_\beta\); the disagreement between both estimates is much larger (up to 1 dex) for the bright end of SFRD\(Pa_\beta\), and less than 0.5 dex at the lower SFRD\(Pa_\beta\) end. This is what we could...
By using the Balmer decrement to dust correct SFRs, we can study a sample of nearby star-forming galaxies and Paschen lines to correct SFRs for dust extinction. Top: SFRDs estimated from the observed Hα and Paβ, without correcting for dust extinction. Bottom: dust-corrected SFRDs, using the Balmer decrement (Hα/Hβ), obtained from the MUSE cube.

Expect, as more star-forming regions are also more obscured by dust. The bottom panel illustrates that the Balmer decrement is not enough of a correction to see the most obscured star-forming regions, with an average offset of $-0.1 \pm 0.2$ dex between SFRD$_{\text{Balmer}}^{\text{Hα}}$ and SFRD$_{\text{Balmer}}^{\text{Paβ}}$. Moreover, the discrepancy on the faint end on both panels may arise from differences in the surface brightness sensitivity of the Hα observations relative to the Paβ, and we would require deeper Paβ observations in the faint regions to study this regime better.

Furthermore, we can directly see the relationship between the dust-corrected SFRD$_{\text{Paβ}}$ (using Hα/Paβ) and the visual extinction inferred with the Balmer-to-Paschen decrement. Figure 12 (right panel) shows the relation between the two for the spatially resolved data of MCG-02-01-051, color coded according to the $A_V$ inferred with the classic Balmer decrement. We see that both quantities correlate, indicating that higher star-forming activity will also be more obscured. On top of this, on the left panel we compare the $A_V$ inferred with each decrement, and we clearly see that the $A_V$ inferred with Paschen lines probes larger optical depths than $A_V$ inferred with Paβ by $>1$ mag, agreeing with works such as L13.

These results agree with previous comparisons with Paschen-line SFRs such as Piqueras-López et al. (2016), where they find that the SFR$_{\text{Paβ}}$ is on average a factor of 3 larger than SFR$_{\text{Hα}}$, even after applying extinction corrections. They conduct this study on a sample of local U/LIRGs, using Brackett and Paschen lines to correct SFR$_{\text{Paβ}}$, and the classic Balmer decrement to dust-correct SFR$_{\text{Hα}}$. Tateuchi et al. (2015) also report that SFR$_{\text{Paα}}$ is systematically larger than SFR$_{\text{Hα}}$ in a sample of nearby star-forming galaxies (33 of them from the IRAS Revised Bright Galaxy Sample catalog), which implies that Paschen lines can reveal star formation that is otherwise obscured for Hα, reaching dustier regions than the optical Balmer lines. Albeit with spectroscopic data and nonspatially resolved observations, Cleri et al. (2022) have Paβ and Hα measurements, and report the same conclusions found in this work.

Besides the nebular lines, we can also study whether Paβ "sees" more star formation than the SFR inferred from the stellar continuum (estimated with our spatially resolved SED fitting code, which is computed directly as the normalization of the two youngest continuum templates, where the reported SFR is averaged over 100 Myr). Figure 13 shows in the vertical axis the difference between these two indicators, as a function of SFRD$^{\text{corr}}_{\text{Paβ}}$, dust corrected with the Balmer-to-Paschen ratio, for galaxy MCG-02-01-051 (top panel) and for the whole sample of our galaxies that belong to GOALS (bottom panel). The individual bins are color coded according to their $A_V$, inferred with the SED fitting code, which applies to the stellar continuum templates. For MCG-02-01-051, we clearly see that the SFR inferred with Paβ is systematically higher than with the stellar continuum for the wide majority of bins, with a mean discrepancy of $-0.3 \pm 0.3$ dex. There is a slight decrease in the difference toward lower SFRD$^{\text{corr}}_{\text{Paβ}}$. On top of this, the bins with higher obscuration traced by the stellar continuum ($A_V$) seem to yield bigger difference...
between both SFR indicators. Besides the fact that the NIR line is less obscured than the optical continuum, the discrepancy between both indicators can also be explained by the different star formation timescales that they both trace. This could be the case particularly for the plot of the whole sample (bottom panel in Figure 13), where the mean discrepancy between the SFR tracers is $-0.3 \pm 0.7$ dex. For small SFRD$^{corr}_{\text{Pa} \beta}$ values, the continuum yields higher star formation. This could be due to the recent star formation being lower than the star formation over the last 100 Myr, or it could be the same effect observed in Figure 11 (where both indicators trace identical timescales), resulting from the depth of the images. On the other hand of high SF activity, where the mean discrepancy goes beyond 1 dex, dust might dominate the difference between the two indicators, as we can see by the enhanced $A_\nu$, as we see that the most obscured bins infer larger SFRDs with the nebular line than with the stellar continuum. This leads us to conclude that near-IR lines are able to see star formation that is invisible to the stellar continuum, reaching further depths than any optical component.

Furthermore, the attenuation experienced by the stars is due to the diffuse ISM, whereas the nebular lines tracing the gas are obscured also by birth clouds, where dust is clumpier and more patchy (Greener et al., 2020). Calabrò et al. (2018) illustrate obscured starburst as an optically thick core with an enclosing layer, emitting NIR and optical nebular lines, which explains both the larger SFR and extinction inferred by NIR lines when compared to optical tracers (Puglisi et al., 2017). The combination of all of these factors results in having differential attenuation and SFRs inferred by nebular lines and the stellar continuum.

With upcoming observations of JWST of Paschen-line emission in galaxies, our results suggest that we will be able to reveal star formation activity that is otherwise currently obscured for optical observations, and it will allow us to paint a more complete picture of the evolution of galaxies and their star formation activity across cosmic time.

4.2.2. Integrated IR SFR Indicators

We have found that Paschen lines can reveal obscured star formation invisible to optical indicators, but now it remains to be explored whether these lines can recover the star formation activity that we can infer with mid- and far-IR indicators, arising from reemitted absorbed UV starlight. Infrared and far-IR luminosities have been shown to be good star formation tracers in dusty starburst galaxies (e.g., Kennicutt, 1998; Kewley et al., 2002). Paschen studies have found a tight agreement between the SFR inferred from dust-corrected Paschen lines and SFR$_{24 \mu m}$, derived from the MIPS/Spitzer 24 $\mu m$ observations (e.g., Piqueras-López et al., 2016). On top of this, a reasonable linear correlation has also been found between Paschen SFRs and the SFR inferred from the infrared luminosity (e.g., Tateuchi et al., 2015). The light that dust absorbs in the UV range of the spectrum is later reemitted at longer wavelengths, in the IR regime. Therefore, IR indicators of reprocessed stellar light have been broadly employed to infer SFRs. Here we focus on the L$_{IR}$ and 24 $\mu m$ emission. We can derive the SFR$_{IR}$ using the calibration by Kennicutt (1998), for a Chabrier (2003) IMF:

$$\text{SFR}_{IR}[M_\odot \text{yr}^{-1}] = 2.5 \times 10^{44} \times L_{IR}[\text{erg s}^{-1}],$$

where $L_{IR}$ is defined as the luminosity in the spectral range 8–1000 $\mu m$. As we do not have multiple available measurements along the IR part of the SED, we cannot infer a spatially resolved analysis with our code. Therefore, we conduct these comparisons in an integrated manner.

First, we compare SFR$_{\text{Pa} \beta}^{corr}$ and SFR$_{IR}$. The SFR$_{\text{Pa} \beta}^{corr}$ inferred from the Paschen-beta line flux following Equation (5), and applying a dust correction using the Balmer-to-Paschen decrement ($H_\alpha$/Pa$\beta$) (calculated on a bin-to-bin basis and then integrating over the whole galaxy). As introduced before, previous studies have found that redder hydrogen recombination lines than H$\alpha$ and H$\beta$, reach further depths than the common Balmer decrement (e.g., Calzetti et al., 1996; Liu et al., 2013), and therefore infer higher obscuration. In agreement with this, in the previous section we have found that Pa$\beta$ systematically traces more star formation than H$\alpha$, even when the Balmer decrement is used for applying a dust correction. For the next comparisons, we use the integrated SFR$_{\text{Pa} \beta}^{corr}$ and we obtain the infrared luminosity values from the GOALS survey measurements (Armus et al., 2009), which can be found on Table 1 in this work.

Figure 14 shows the comparison between the extinction-corrected SFR inferred with Paschen lines and SFR$_{IR}$ for various studies. The targets from our sample are indicated with the diamond symbol, blue colored if they host an AGN and red colored if not.

![Figure 14](image-url) Extinction-corrected SFR$_{\text{Pa} \beta}^{corr}$ as a function of the SFR inferred from the infrared luminosity. The various data sets are detailed in the main text. Our sample is indicated by the diamond symbol, blue colored if they host an AGN and red colored if not.
VLT-SINFONI, using Brackett and Paschen lines to dust-correct SFR$_{\text{Pa\alpha}}$ and a Calzetti et al. (2000) attenuation curve with a 0.44 ratio between the ionized gas and stellar continuum applied. The green upward triangles correspond to local LIRGs from Alonso-Herrero et al. (2006), obtained measuring the Pa$\alpha$ fluxes and comparing them with their H$\alpha$ and Br$\gamma$ measurements, respectively, and estimating the extinction to the gas using the Rieke & Lebofsky (1985) extinction law and a foreground dust screen model. The orange circles are measurements of normal galaxies from the Nearby Field Galaxy Survey (NFGS; Kewley et al. 2002). For these galaxies the SFR is inferred with H$\alpha$ and dust corrected with the classic Balmer decrement. The maroon stars correspond to H II galaxies from the sample of local LIRGs presented in Tateuchi et al. (2015), where they use the H$\alpha$/Pa$\alpha$ ratio to correct for the extinction their Pa$\alpha$ measurements and a Calzetti et al. (2000) attenuation curve with $R_V = 4.05$.

Overall, we find a considerable agreement between the SFR inferred from Paschen lines and the IR luminosity, with some targets having higher SFR$_{\text{IR}}$, as also encountered and discussed in, e.g., Piqueras-López et al. (2016). Tateuchi et al. (2015) also find a systematic offset of $-0.07$ dex of SFR$_{\text{Pa\alpha}}$ with respect to SFR$_{\text{IR}}$, and a scatter of $0.27$ dex. The targets presented in this work seem to agree well with all previous published results. The discrepancy between both indicators for our galaxies is $-0.04 \pm 0.23$ dex, with the majority of targets lying on the one-to-one relation. We also find some extreme cases where both indicators considerably disagree. This could be due to very high obscuration, or other extreme environments within the galaxy, such as is the case for Arp 220, a known extreme starbursty ULIRG, which is the biggest outlier in Figure 14. Previous studies such as Calabrò et al. (2018), report that SFRs inferred with tracers from the UV to the NIR are systematically underestimated when compared to SFR$_{\text{IR}}$ in ULIRGs, which we also find here.

The discrepancy that we find could also be due to the choice of radii within which we integrate the Pa$\beta$ flux and its difference with respect to the GOALS choice to integrate L$_{\text{IR}}$ in these targets. Furthermore, ULIRGs infrared luminosity may originate from very compact regions (Pereira-Santaella et al. 2021).

On the other hand, the SFR$_{\text{IR}}$ might trace star formation occurring in longer timescales than the most recent star formation (Calabrò et al. 2018), which is traced by hydrogen recombination lines arising from H II regions, such as the ones we explored before when comparing the SFR from the optical stellar continuum and the lines. This could be the case for example for the NFGS sample (Kewley et al. 2002), which appears to have systematically lower SFR$_{\text{Pa\alpha}}$ than SFR$_{\text{IR}}$, while our results are closer to the 1:1 line, on average. This might be due to their SFRs being inferred with H$\alpha$ and dust corrected with the Balmer decrement, instead of redder Paschen lines. Or it could also be explained by an age effect, i.e., we see a recent star formation that was a systematic factor lower than the star formation over the last 100 Myr. This is mainly due to the fact that old stellar populations can still heat the dust that emits in the far-IR, a known effect that has been observed at the level of a factor of $\sim$2 in the SFR difference.

Tateuchi et al. (2015) attribute the discrepancy between the inferred SFRs to high dust obscuration, IR cirrus component or the presence of AGNs in the galaxies, which could be possible sources of systematic differences. If we focus on our sample, the targets that are known to host an AGN do not exhibit a particular trend in Figure 14. The presence of an AGN could explain the discrepancy for two out of six targets, but the other four are on top of the 1:1 agreement. Therefore, we cannot report a systematic trend on the SFR$_{\text{Pa\beta}}$ and SFR$_{\text{IR}}$ relationship due to the presence of an AGN in our galaxies.

Besides using the L$_{\text{IR}}$ to infer the SFR, we can also use another mid-IR indicator, namely, the emission from the continuum at 24 $\mu$m. We use Equation (10) presented in Rieke et al. (2009), to infer the SFR from the 24 $\mu$m luminosity:

$$\text{SFR}_{24\mu m} [M_\odot \text{yr}^{-1}] = 7.8 \times 10^{-10} \times L_{24\mu m} [L_\odot].$$  (7)

We can now compare SFR$_{\text{Pa\beta}}$ and SFR$_{24\mu m}$. Figure 15 shows the resulting comparison. We retrieve a similar linear correlation to the previously discussed with SFR$_{\text{IR}}$. For our targets, the discrepancy between both indicators is $0.14 \pm 0.32$ dex, so the 24 $\mu$m emission and Pa$\beta$ provide consistent SFR estimates. Previous studies have found similar conclusions, as well as deviations at the high-luminosity end (e.g., Alonso-Herrero et al. 2006; Rieke et al. 2009; Piqueras-López et al. 2016). Figure 15 also includes results from previous studies, to be able to place our conclusions into context. As for the SFR$_{\text{IR}}$ comparison displayed before, these studies use Pa$\alpha$ to infer SFRs instead of Pa$\beta$ for our study. In Figure 15, the turquoise squares (ULIRGs) and violet upward triangles (LIRGs) are data from PL+16. The green circles correspond to Space Infrared Telescope Facility Nearby Galaxy Survey (SINGS; Kennicutt et al. 2003) galaxies from Calzetti et al. (2007). The orange downward triangles are measurements from individual star-forming regions of M51 from Calzetti et al. (2005). The available 24 $\mu$m galaxies from our sample are displayed with white diamonds and can be seen in Figure 15 perfectly agreeing with the other works, as well as falling on top of the one-to-one line, on average. As before, we do not see a trend in the SFR relationship due to the presence of an AGN. It is quite remarkable to see the agreement over almost 6 orders of magnitude in SFR$_{24\mu m}$, and covering sizes from individual star-forming regions in M51 to integrated LIRGs and ULIRGs. On the other hand, we would expect both SFRs to agree if the 24 $\mu$m emission was entirely due to star formation alone, as SFR$_{24\mu m}$ is calibrated from Paschen recombination lines (e.g., Calzetti et al. 2007). The contribution from evolved older stellar populations could also explain the deviations from the one-to-one trend in both comparisons in this section. Various studies imply that SFRs inferred from IR tracers are overestimated due to the emission from the dust heated by old stars (see, e.g., Fumagalli et al. 2014). On top of this, the uncertainty in the dust temperature determination and possible evolution with redshift, leads to considerable uncertainties on the inferred physical galaxy properties, such as the obscured SFR and L$_{\text{IR}}$ (e.g., Sommovigo et al. 2020, 2022), which is an important factor to consider particularly at higher redshifts. All tabulated values from our sample used for Figures 14 and 15 can be found on Table 2.

In summary, we report that the SFR inferred with dust-corrected Pa$\beta$ emission can recover the star formation estimated via mid-IR tracers, therefore being enough to estimate the SFR for each individual galaxy, in an integrated sense. A good agreement is found both with the MIPS 24 $\mu$m emission and the SFR$_{\text{IR}}$, following previously published results. Other works in the literature indicate that SFRs derived from MIPS 24 $\mu$m + UV emission may overestimate the SFR when compared to the SFR derived from modeling the entire UV-to-IR SEDs, especially at the low-SFR end (e.g., Leja et al. 2019;
5. Summary and Conclusions

In this work we have presented a sample of 53 local star-forming galaxies, covering the SFR range from normal star-forming spirals to LIRGs and up to ULIRGs, 24 belonging to the GOALS survey (Armus et al. 2009). For each target we have HST narrowband observations targeting the H$\alpha$ and Pa$\beta$ emission lines, as well as nearby broadband continuum filters. This allows us to constrain the dust obscuration in these objects with the Balmer-to-Paschen decrement, which has been demonstrated to reach further depths and therefore obscuration than the commonly used Balmer decrement (H$\alpha$/H$\beta$). This provides the first systematic study on a large sample of very-high-quality observations, with this level of high-resolution and for the first time, both subkiloparsec-resolved H$\alpha$ and Pa$\beta$ measurements.

For 24 of our targets that are also part of the GOALS survey of local luminous and ultraluminous infrared galaxies, we have presented a methodology to treat spatially resolved observations, as well as obtaining robust parameters from local or high-z photometric observations with our SED fitting technique. Our code provides trustworthy emission-line fluxes from photometric measurements that match those obtained from direct spectra on the same targets (within 0.05 dex). Our inferred physical parameters match those estimated with other SED fitting codes, at a much smaller computational cost when compared to, i.e., Prospector, and help us analyze the nature of our targets.

We have performed an in-depth analysis of the different SFR indicators that we can infer to probe the star formation in our galaxies at various wavelengths and timescales. We have demonstrated in a spatially resolved manner that the SFRD inferred with Pa$\beta$ is systematically higher than with H$\alpha$, even when a dust correction is applied using the Balmer decrement, with a mean offset of 0.1 ± 0.2 dex. Our results agree with previous published works, although this had not been tested on a bin-to-bin basis before. Furthermore, Pa$\beta$ seems to recover more star formation than the optical stellar continuum in the most obscured parts of each galaxy. This could also indicate a bursty nature of our sources, as the SFR inferred with the stellar continuum provides the star formation convolved over a larger period of time. Besides this, the emission from the stellar continuum and the nebular lines come from different regions within the galaxies.

On top of this, we have tested whether SFR$_{Pa\beta}$ can recover the star formation inferred by IR indicators. We find consistent SFR estimates both with the emission traced by the 24 $\mu$m continuum (with a ratio 0.14 ± 0.32 dex) and with the SFR$_{H\alpha}$ (with a ratio 0.04 ± 0.23 dex). This agrees with previous studies on the different SFR tracers, and gives us confidence in using Paschen lines to paint a more complete picture of star formation at all redshifts.

We obtain high-resolution and robust extinction maps for all targets, probing unusually high A$_V$ inferred by the gas, especially toward the core of the galaxies. Forthcoming publications will analyze this in detail, in particular the differential attenuation experienced by the gas (traced by the Balmer-to-Paschen decrement) and the stars (traced by the stellar continuum). Accurately inferring large obscuration in galaxies could yield very exciting new avenues, such as discussed in Calabrò et al. (2018), where it is introduced that one could identify mergers by their extreme obscuration levels. At high redshift, one cannot rely in the morphological signs to identify merging galaxies, and severe values of A$_V$ have not been able to be explained by other mechanisms. Upcoming JWST observations of NIR lines could help us test this idea and possibly find a new way of identifying high-z mergers.
Our study paves the way to very exciting upcoming works that will benefit from the first high-quality spatially resolved observations at higher redshifts to be obtained with JWST. This telescope will be able to observe Paschen-line emission in high-$z$ galaxies at $z > 1$, breaking the ice for extending studies and methodologies like the ones presented in this work to higher redshifts. This will aid us in our pursuit to understand how galaxies form and evolve across cosmic time, helping us constrain their star formation activity by seeing through the dust like we have not been able before. Paschen lines will also strain their star formation activity by seeing through the dust galaxies form and evolve across cosmic time, helping us constrain their star formation activity by seeing through the dust like we have not been able before. Paschen lines will also strain their star formation activity by seeing through the dust.

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**Facilities:** HST (ACS), HST (WFC3).

**Software:** Astropy (Astropy Collaboration et al. 2013), Matplotlib (Hunter 2007), NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020), Grizli (Brammer & Matharu 2021).

### Appendix A

**Voronoi Binning**

As stated in Section 3.1, we develop an adaptation of the Voronoi binning procedure from Cappellari & Copin (2003) to be able to perform the binning in large data sets and in regimes of low S/N per original data point.

Our hybrid block-averaging approach starts by defining a reference image that is used in the binning and selecting the desired S/N threshold. We choose this to be the narrowband image that targets Paβ, usually being F130N or F132N, as it is important for our further use of the line fluxes to obtain robust S/N line detections in the narrowband images, particularly Paβ, being usually fainter than Hα. The code starts by creating a block averaged image, where each block has $32 \times 32$ original pixels. We mask any pixels where these large bins have S/N values less than a minimum threshold, which is one of our binning parameters. Then, we run Cappellari & Copin (2003) optimal Voronoi 2D binning algorithm on this large blocked image. We adopt as a Voronoi bin anything with more than one individual (blocked) pixel ($N > 1$), and these pixels are now “frozen” in the binning. Individual pixels that satisfy the target S/N (i.e., $N = 1$ blocked bins) are sent to the next step, which consists of reducing the block size by a factor of 2 (e.g., $16 \times 16$ at the second stage). Pixels in blocks where the S/N does not reach the target S/N, and therefore the Voronoi code bins multiple blocks together, are not sent to the next step and remain in that assigned Voronoi bin. The code repeats these steps until the desired minimum bin size is achieved (e.g., if the minimum possible size is wanted, it stops when it reaches $1 \times 1$, i.e., native pixels). For our study we stop at $2 \times 2$ pixels as the minimum size of a bin, reducing the number of points to be able to perform further analyses, but at the same time not losing drastically the high resolution in our images. For example, for a $2 \times 2$ pixels bin, which would be 0.″2 across, we still achieve a resolution of 80 pc at $z \sim 0.02$.

Once we create the Paβ narrowband binned image, we applied the derived binning to the other filter images available for that galaxy. However, this means that for some bins the target S/N criterion is not necessarily met in all bands, which could later on affect the robustness of the derived physical parameters in that bin. By imposing the S/N threshold on the Paβ narrowband image, which is usually the band with least S/N across the image, we reduce this issue. Nonetheless, it is important to have the same binning in all images to be able to perform different studies on them. Specific information on how to run the binning code can be found on the Github repository.18

### Appendix B

**SED Fitting**

We develop an adaptation of the Python version of EAZY19 (Brammer et al. 2008), which includes an extra-reddening grid, which allows four continuum templates to fit $A_V$ from 0.0 to 5.0, and two emission-line templates, $H\alpha$+[N II] and Paβ. The set of templates that we use are shown in Figure 16. Analogous to the stepwise SFH parameterization of Prospector (Leja et al. 2017), the continuum templates are generated for stepwise time bins between 0, 50, 200, 530 Myr, 1.4 Gyr with a constant SFR across each bin. The line templates are created as Gaussian peaks with a continuum set to zero and a sigma width of 100 km s$^{-1}$. We set the [N II]/Hα ratio to 0.55. We note that these templates are not identical to those that EAZY uses for photometric redshift estimates. Here we fit explicitly for dust reddening, whereas in EAZY the reddening is a property of the linear combination of basis templates that have diversity of SFH and dust reddening (Brammer et al. 2008).

Our code receives a catalog as input (which can have multiple targets, or in our study it has multiple bins to study spatially resolved properties), performs the fit, and outputs the inferred physical estimates. The SED fitting code works as follows. First, it imports the templates (that can be defined by the user, as can multiple other features that follow) and the photometric measurements. For this, it follows how EAZY reads in catalogs given by the user. The reddening grid is then defined, and the templates are integrated through the filter bandpass to produce synthetic

---

18 https://github.com/claragimenez/voronoi
19 https://github.com/gbrammer/eazy-py
Figure 16. Top: set of continuum templates that we use in our SED fitting code. Bottom: Hα+[N II] (left) and Paβ (right) pure line emission templates.

photometry. Then the fit at each point of the grid and bin is performed, calculating the resulting $\chi^2$ between the observed data and synthetic photometry and saving it at each step. After this, the covariance matrix is calculated, and we draw 1000 random and synthetic photometry and saving it at each step. After this, the full sampling of each parameter estimate of the parameter value in each bin is evaluated in the full grid space. From the 0.5 percentile we get an uncertainty and values of our inferred physical properties by with the cumulative sum of the normed PDF and each parameter uncertainties and values of our inferred physical properties by.

Figure 17. Histograms of the [N II]/Hα ratio for the six galaxies that are part of the GOALS survey, as measured in the MUSE IFU cube. The value we adopt for the ratio is indicated with a black dashed line on the histogram, and the gray shaded region shows the 1σ interval around of the mean. The y-axis is normalized.

photometric data. Here we present the resulting [N II]/Hα histograms for the five additional targets that are not presented in Section 3.4.1. Figure 17 shows the histograms for the targets Arp 220, IRAS13120-5453, IRAS18090+0130, MCG-02-01-051 (presented also in the main text, displayed with a different color), NGC 6240, and NGC 7592. Half of the targets agree with our adopted value of 0.55 within 1σ of the mean, whereas the other three show quite extreme [N II]/Hα, with the majority or all bins having [N II] > Hα across the galaxy, as found in other works (e.g., Perna et al. 2021).

The systematic shift in $A_V$, $\Delta A_V$, caused by using two different [N II]-to-Hα correction factors, $f_{\text{corr}}$, will be given by:

$$
\Delta A_V = C_1 \log \left( \frac{f_{\text{corr}}}{f_{\text{corr}}^2} \right),
$$

where $C_1$ is the following constant:

$$
C_1 = R_V \times \frac{2.5}{k(\text{Pa}\beta) - k(\text{H} \alpha)}.
$$

The correction factor is computed as follows:

$$
f_{\text{corr}} = \frac{\text{H} \alpha/[\text{N II]}}{\text{H} \alpha/[\text{N II]} + 1}.
$$

The resulting Hα flux that is corrected for [N II] contamination is given by $f_{\text{corr}} = f_{\text{corr}}^2 \times f_{\text{H} \alpha/[\text{N II]}},$ where the last term is the measured combined [N II]+Hα flux.

Appendix C
MUSE Archival Data

As discussed in Section 3.4.1, six of the galaxies in our sample have archival MUSE observations that we use to test the reliability of our inferred Hα fluxes from the HST.

Appendix D
Filter Coverage

Here we present a test of how the specific filter coverage available for each object can affect the emission-line maps derived with our method. We want to test if the different filter widths or number of available filters affect our ability to
recover the physical properties that we infer, such as the Hα line flux. For this, we make use of the archival MUSE cube for MCG-02-01-051 (see also Section 3.4.1). We can integrate the MUSE spectra through various filter bandpasses to produce synthetic images. For MCG-02-01-051, we have six HST bands available (F673N, F130N, F132N narrow and F435W, F814W, F110W broad). We add synthetic observations from the MUSE cube of the HST ACS/WFC F555W, F606W, and F775W bandpasses, to better sample the optical continuum. We then run our binned SED fitting software with the same set-up as before with the observed HST and synthetic MUSE images.

Figure 18 displays the comparison of the resulting Hα flux inferred with both estimates, in maps (top panels) and as a scatter plot (bottom panel). We find that the emission-line map derived from the limited available HST data is fully consistent with the best-case scenario with additional broadband optical filters (with a median log ratio of 0.06 ± 0.07 dex). When considering the rest of the inferred physical parameters, both runs are consistent, having less than 0.3 dex off between them when inferring the SFR, the stellar mass, or the $A_V$.

In order to fully constrain the SFH and dust obscuration of the continuum, we prefer to have a broader wavelength coverage. Nonetheless, we conclude that with the average filter coverage of our sample, we can adequately infer physical properties with our SED fitting code.

Appendix E
Individual Galaxies

Figures 19–41 display the three-color composites, Hα and Paβ emission-line maps, extinction maps inferred from the gas and the stellar population, as well as SFR and stellar mass maps for each galaxy presented in this paper.
Figure 19. Output of the spatially resolved SED fit on Arp 220. The top row, from left to right, shows the RGB image (built combining three broadband filters), the stellar mass density map, and the SFRD maps inferred with the stellar continuum and with the Paβ emission-line flux. The bottom row shows the resulting Hα and Paβ surface density flux maps, as well as the A_v inferred from the empirical Balmer-to-Paschen decrement, and the stellar continuum. The cross is centered on the brightest F110W pixel. The physical scale is indicated on the A_v continuum panel (bottom right).

Figure 20. Maps of the physical properties inferred with our SED fitting code for ESO550-IG025. See Figure 19 for more details.
Figure 21. Maps of the physical properties inferred with our SED fitting code for IRAS03582+6012. See Figure 19 for more details.

Figure 22. Maps of the physical properties inferred with our SED fitting code for IRAS08355-4944. See Figure 19 for more details.
Figure 23. Maps of the physical properties inferred with our SED fitting code for IRAS12116-5615. See Figure 19 for more details.

Figure 24. Maps of the physical properties inferred with our SED fitting code for IRAS13120-5453. See Figure 19 for more details.
Figure 25. Maps of the physical properties inferred with our SED fitting code for IRAS18090+0130. See Figure 19 for more details.

Figure 26. Maps of the physical properties inferred with our SED fitting code for IRAS23436+5257. See Figure 19 for more details.
Figure 27. Maps of the physical properties inferred with our SED fitting code for IRASF10038-3338. See Figure 19 for more details.

Figure 28. Maps of the physical properties inferred with our SED fitting code for IRASF16164-0746. See Figure 19 for more details.
Figure 29. Maps of the physical properties inferred with our SED fitting code for IRASF16399-0937. See Figure 19 for more details.

Figure 30. Maps of the physical properties inferred with our SED fitting code for MCG-02-01-051. See Figure 19 for more details.
Figure 31. Maps of the physical properties inferred with our SED fitting code for MCG+12-02-001. See Figure 19 for more details.

Figure 32. Maps of the physical properties inferred with our SED fitting code for NGC 2146. See Figure 19 for more details.
Figure 33. Maps of the physical properties inferred with our SED fitting code for NGC 2623. See Figure 19 for more details.

Figure 34. Maps of the physical properties inferred with our SED fitting code for NGC 5256. See Figure 19 for more details.
Figure 35. Maps of the physical properties inferred with our SED fitting code for NGC 5331. See Figure 19 for more details.

Figure 36. Maps of the physical properties inferred with our SED fitting code for NGC 6090. See Figure 19 for more details.
Figure 37. Maps of the physical properties inferred with our SED fitting code for NGC 6240. See Figure 19 for more details.

Figure 38. Maps of the physical properties inferred with our SED fitting code for NGC 6670. See Figure 19 for more details.
Figure 39. Maps of the physical properties inferred with our SED fitting code for NGC 6786. See Figure 19 for more details.

Figure 40. Maps of the physical properties inferred with our SED fitting code for NGC 7592. See Figure 19 for more details.
Appendix F

Additional Galaxies

Due to the availability of $L_{IR}$ and 24 $\mu$m flux measurements, we exclude from our analysis 29 additional galaxies. These targets also often have spatial extent larger than the FOV of the instrument. Nonetheless, we have processed the HST data of these additional targets following the same reduction process explained in Section 2, and the reduced mosaics are also publicly available. Table 3 summarizes the filter coverage of the additional targets.

Table 3

| Target          | R.A. (deg) | Decl. (deg) | $z^a$ | log($M_{HI}/M_\odot$) | UV WFC3/UVIS | Optical WFC3/UVIS, ACS/WFC | IR WFC3/IR |
|-----------------|------------|-------------|-------|------------------------|--------------|---------------------------|------------|
| ESO338-IG004    | 291.99308  | −41.57523   | 0.0095| ...                    | f550M, f656N | f625W, f673N              | f110w, f130n |
| MCG+00-29-023   | 170.30109  | −2.984167   | 0.0247| 11.4$^b$               | f435W, f555W, f606W, f658N, f673N, f689M, f814W | f110w, f128N |
| M51             | 202.46958  | 47.19526    | 0.0016| 10.4$^b$               | f225W, f275W, f336W | f435W, f555W, f606W, f658N, f673N, f689M, f814W | f110w, f128N |
| M82             | 148.96846  | 69.67970    | 0.0007| 10.8$^b$               | f225W, f275W, f336W | f435W, f487N, f502N, F547M, f555W, f658N, f660N, f673N, F814W | f110w, f128n, f130w, f160W, f164N |
| M83             | 204.25383  | −29.86576   | 0.0017| 10.3$^b$               | f225W, f336W, f373N | f435W, f438W, F487N, f502N, F547M, f555W, f657N, f658N, f660N, f666N, f673N, f814W | f110w, f125W, f128N, f140W, f160W, f164N |
| NGC 0253        | 11.8806    | −25.2888    | 0.0009| 10.4$^b$               | f475W, f606W, f814W | f475W, f606W, f814W | f110w, f128N, f130W, f160W, f164N |
| NGC 1140        | 43.63976   | −10.0285    | 0.0050| ...                    | F625W, f658N | F625W, f658N              | f110w, f128N, f160W, f164N |
| NGC 1396        | 54.52743   | −35.43992   | 0.0029| ...                    | f475W, f606W, f625W, f658N, f850LP | F621M, f657N | f110w, f128n |
| NGC 1482        | 58.6622    | −20.50245   | 0.0063| 10.8$^b$               |                  | F621M, f657N              | f110w, f128N, f160W, f164N |

$^a$ http://cosmos.phy.tufts.edu/dustycosmos/

Figure 41. Maps of the physical properties inferred with our SED fitting code for VV340A. See Figure 19 for more details.
Table 3
(Continued)

| Target   | R.A. (deg) | Decl. (deg) | z* | $\log \left( L_\text{IR} / L_\odot \right)$ | UV WFC3/UVIS | Optical WFC3/UVIS, ACS/WFC | IR WFC3/IR |
|----------|------------|-------------|----|------------------------------------------|--------------|---------------------------|------------|
| NGC 2551 | 126.20956  | 73.41200    | 0.0077 | ...                                      | F625W, F658N | F160W, F164N               |
| NGC 2681 | 133.38641  | 51.31371    | 0.0023 | 9.5b                                     | F658N, F814W | f110w, f128n               |
| NGC 2841 | 140.51106  | 50.97648    | 0.0019 | 10.1b                                    | F225W, F336W | F110W, f128n, f139n, F610W |
| NGC 2985 | 147.59264  | 72.27865    | 0.0043 | 10.2b                                    | F658N, F814W | f110w, f128n               |
| NGC 3358 | 160.88763  | −36.41071   | 0.0101 | ...                                      | f625w, f665n | f110w, f128n, f130n        |
| NGC 3738 | 173.95085  | 54.52373    | 0.0007 | ...                                      | F438W, F606W, F658N, F814W | f110W, F128N, F160W, F164N |
| NGC 4038 | 180.47084  | −18.86759   | 0.0056 | 10.8b                                    | F336W        | F110W, F128N, F160W, F164N |
| NGC 4214 | 183.91323  | 36.32689    | 0.0010 | 8.9b                                     | F225W, F336W, F373N | F110W, F128N, F160W, F164N |
| NGC 5128 | 201.36506  | −43.01911   | 0.0018 | 10.1b                                    | F225W, F336W | F128N, F160W, F164N        |
| NGC 6217 | 248.16340  | 78.19821    | 0.0046 | 10.3b                                    | F435W, F625W, F658N, F814W | f110w, f128n |
| NGC 6690 | 278.70935  | 70.25389    | 0.0016 | ...                                      | F625W, F658N | f110w, f128n               |
| NGC 6946 | 308.718    | 60.1539     | 0.0001 | 10.9b                                    | F435W, F547M, F555W, F625W, F658N, F673N, F814W | F110W, F128N, F160W, F164N |
| NGC 6951 | 309.30865  | 66.10564    | 0.0048 | 10.6b                                    | F555W, F658N, F814W | f110w, f128n |
| NGC 7090 | 324.12027  | −54.55732   | 0.0028 | 9.2b                                     | F606W, F625W, F658N, F814W | f110w, f128n |
| PGC4798 | 20.01106   | 14.36107    | 0.0314 | 11.6b                                    | F435W, F673N, F814W | f110w, f132n |
| SDSS−J110501.98 +594103.5 | 166.28528  | 59.68431    | 0.0338 | ...                                      | F336W        | f110w, f132n               |
| SDSS−J112823.84 +573243.4 | 262.09933  | 57.54539    | 0.0290 | ...                                      | F336W        | f110w, f132n               |
| SDSS220141.64 +115124.3 | 330.4235   | 11.85675    | 0.0296 | ...                                      | FQ508N, F621M, F673N, F763M | f110w, f132n |
| UGC5626  | 156.11644  | 57.39251    | 0.0085 | ...                                      | F625W, F658N | f110w, f130n               |

Notes. All targets have available reduced multiband data, but they are excluded in the analysis presented in this work. The filters added by the Cycle 23 SNAP program (HST-14095; Brammer 2015) are indicated with lower-case letters, whereas the rest are archival data.

a The redshifts were extracted from the NASA/IPAC Extragalactic Database (NED), though we note that some of the closest targets are not necessarily in the Hubble flow.

b Infrared luminosity from the IRAS Revised Bright Galaxy Sample (Sanders et al. 2003).

c Infrared luminosity from the KINGFISH Survey (Kennicutt et al. 2011).

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