

Galaxies decomposition with spiral arms – I: 29 galaxies from S⁴G

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ABSTRACT

Spiral structure can occupy a significant part of the galaxy, but properly accounting for it in photometric decomposition is rarely done. This may lead to significant errors in the parameters determined. To estimate how exactly neglecting the presence of spiral arms affects the estimation of galaxy decomposition parameters, we perform fitting of 29 galaxies considering spiral arms as a separate component. In this study, we utilize 3.6 μm -band images from the S⁴G survey and use a new 2D photometric model where each spiral arm is modelled independently. In our model, the light distribution both along and across the arm and its overall shape can be varied significantly. We analyse the differences between models with and without spiral arms, and show that neglecting spiral arms in decomposition causes errors in estimating the parameters of the disc, the bulge, and the bar. We retrieve different parameters of the spiral arms themselves, including their pitch angles, widths, and spiral-to-total luminosity ratio, and examine various relations between them and other galaxy parameters. In particular, we find that the spiral-to-total ratio is higher for galaxies with more luminous discs and with higher bulge-to-total ratios. We report that the pitch angle of spiral arms decreases with increasing bulge or bar fraction. We measure the width of the spiral arms to be 53 per cent of the disc scale length, on average. We examine the contribution of the spiral arms to the azimuthally averaged brightness profile and find that spiral arms produce a ‘bump’ on this profile with a typical height of 0.3–0.7 mag.

Key words: galaxies: spiral.

1 INTRODUCTION

The spiral arms of disc galaxies are remarkable structures with regions of ongoing star formation which are embedded into a fainter stellar disc. Studying spiral galaxies is of great importance as these galaxies represent a significant part (about 75 per cent of galaxies brighter than $M(B) = -20$ mag) of the local Universe (Conselice 2006). Apart from spiral arms, the most prominent subsystems of disc galaxies, that are easily distinguishable in images, are a central spheroidal bulge and a flat extended stellar disc. A comprehensive analysis of the galactic structure requires measurements of the parameters (luminosities, spatial scales, etc.) of these subsystems. However, since physical components of a galaxy are embedded in each other and only a combined image of the sum of all components is observed, the structural analysis of the galaxies presents a complex computational problem. One possible solution to this issue is the so-called decomposition, which allows one to distinguish the light coming from the different galactic components.

The key ingredient of the decomposition implies describing the surface brightness distribution of galactic components by analytical

functions with specific parameters. The optimal values of these parameters can be found, and information about the physical components thus can be inferred (for example, see Erwin 2015; Méndez-Abreu et al. 2017). Due to its relative simplicity, bulge + disc decomposition is the most common approach to fit a galaxy image. For the bulge component, the de Vaucouleurs profile (de Vaucouleurs 1948) or the more general Sérsic function (Sérsic 1968) are often used, whereas the disc is usually described by an exponential profile suggested by Freeman (1970). Bulge + disc decomposition has a moderate computational intensity and can be deployed as an automatic procedure. As a result, thousands and even millions of galaxies have been decomposed into several structural components (Simard et al. 2011; Bizyaev et al. 2014; Lang, Hogg & Mykytyn 2016). The obtained data allowed these authors to identify many physical scaling relations, such as the connection between the bulge fraction and the kinematics (Cappellari et al. 2013) or the supermassive black hole mass (Vika et al. 2012), or relations between the bulge surface brightness, luminosity, and half-light radius (Fisher & Drory 2010), which appeared to be different for bulges and pseudobulges (Gadotti 2009).

However, real galaxies often exhibit a more complex structure that cannot be reliably described by just two components, such as a disc and a bulge. Numerous studies have been focused on applying more

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advanced photometric models in galaxy decomposition. For example, the central regions often contain a bright component (a second bulge, a nuclear disc, etc.) and one should use an additional Sérsic profile (D’Souza et al. 2014; Erwin et al. 2021) to properly represent it in the model. Sometimes, the contribution of the active galactic nucleus is modelled using an unresolved point source (Gadotti 2008) or a nuclear disc (Gadotti et al. 2020). For disc components, more precise models are often adopted, with breaks of different types (Laine et al. 2014), or with inner truncation justified by the presence of a bar or by quenching (Papaderos et al. 2022). Additional thick or thin disc components and flaring can also be added (Mosenkov et al. 2021). For edge-on galaxies, boxy or peanut-shaped (B/PS) bulges are often observed and are modelled via a separate component (Smirnov & Savchenko 2020; Marchuk et al. 2022). Despite the long list of aforementioned modifications, in some cases their inclusion may not be sufficient to accurately model a particular galaxy, since non-axisymmetric features may also be present (Peng et al. 2010). In particular, spiral arms exhibit a wide variety of shapes with different winding tightness and width, thus making it difficult to properly account for spiral arms via photometric modelling. Moreover, the spiral structure is not always symmetric and the number of spiral arms varies from galaxy to galaxy. This diverse appearance is reflected in a number of classifications that were created to group them. Elmegreen & Elmegreen (1982) suggested a complex scheme in which there were a total of 12 different types. The classification was later revised in Elmegreen & Elmegreen (1987), where the number of classes was reduced to 10 (for example, details of the bar presence were excluded from classification). In Elmegreen (1990), this classification was boiled down to three main classes that describe the general appearance of spirals. These include grand design galaxies that host two prominent spiral arms, multiple armed galaxies that have more than two distinguishable arms, and flocculent galaxies consisting of many fragmentary and fuzzy arms. This complexity of spiral structure indicates that an analytical function for describing spiral arms in galaxies should be very flexible, have a rather large number of free parameters and, hence, be difficult to fit.

Spirals are prominent, extended features in galaxy discs, so their contribution to the galaxy’s luminosity is far from negligible, especially in grand design galaxies, where they account for up to 40 percent of the total galactic luminosity (Savchenko et al. 2020). Therefore, it is reasonable to expect that when we neglect their presence in our modelling, this may lead to systematic errors in the decomposition results. Moreover, due to the complexity of the appearance of spiral arms in galaxies, these errors are hard to estimate without a proper model for the spiral structure. The literature on this subject is scarce, and the existing studies are quite controversial. For example, some studies report that bulge parameters remain unchanged when spiral arms are added to model, while others state that the neglect of spiral arms causes significant biases in them (Läscher, Ferrarese & van de Ven 2014; Gao & Ho 2017; Lingard et al. 2020; Sonnenfeld 2022).

Some effort has been made to estimate inaccuracies of ‘classical’ decomposition when spiral arms are not taken into account, by examining artificial images of galaxies (Lingard et al. 2020; Sonnenfeld 2022). Problems with this approach arise from the fact that mock galaxies look too simplified and unnatural when compared to real objects. Another approach used for decomposition is formulated in Peng et al. (2010). In the GALFIT framework, spiral arms are modelled as Fourier modes, modified by a rotation function of various forms. This approach is much more credible and robust even for spiral galaxies with complex structure. However, it is hard to use this model in practice, so this type of decomposition was applied only in

a few studies with a handful of galaxies (Davis et al. 2012; Läscher, Ferrarese & van de Ven 2014; Gao & Ho 2017). Moreover, such a method is unable to properly trace pitch angle variations that are often observed in real galaxies (Savchenko & Reshetnikov 2013; Savchenko et al. 2020), and to produce a highly asymmetric spiral structure observed in many galaxies (Conselice 1997). In general, the results from the aforementioned studies, concerning the importance of spiral structure, indicate that there is certainly room for improvement of the photometric model.

In this paper, first in series, we conduct a study of a sample of spiral galaxies using a new model of spiral arms, which is flexible enough to fit different forms of spiral structure. We aim to determine what kind of decomposition errors arise when spiral arms are not properly accounted for in decomposition. In addition, we are able to obtain the full parametric description of spiral arms, which is equally important. Since we use a model with the physically motivated parameters which are easy to interpret, this allows us to measure a plenty of parameters of spiral arms themselves, such as their widths or pitch angles. Measuring such parameters in the process of decomposition has another advantage because the model of the spiral arms is fully treated in this case (see for comparison Savchenko et al. 2020 who measured the parameters of spiral structure using residual images of spiral arms obtained after subtracting an azimuthally averaged model from the galaxy image).

Our paper is organized as follows. In Section 2, we describe the sample of galaxies and observational data used. In Section 3, we describe the model of spiral arm. Section 4 provides details about our decomposition and validation of our results. Our results concerning systematic errors of classical decomposition and statistics of the parameters of spiral arms (along with the general structural parameters) are discussed in Sections 5 and 6, respectively. We interpret our results in Section 7 and summarize our findings and conclusions in Section 8.

2 THE SAMPLE AND DATA

For this study, we selected a sample of spiral galaxies from the *Spitzer* Survey of Stellar Structure in Galaxies (S⁴G; Sheth et al. 2010). S⁴G contains more than 2300 nearby ($d < 40$ Mpc), bright ($M(B) < -15.5$ mag) and angularly extended ($D_{25} > 1$ arcmin) galaxies, located far from the Galactic plane ($|b| > 30^\circ$). S⁴G provides images at 3.6 and 4.5 μm (we use only 3.6 μm) with pixel size of 0.75 arcsec and angular resolution about 2 arcsec. In terms of depth, S⁴G images reach $\mu_{3.6\mu\text{m}}(\text{AB})(1\sigma) \sim 27$ mag arcsec⁻² (about $1 M_\odot \text{pc}^{-2}$). S⁴G is a suitable survey for this study because it covers a near-infrared part of the spectrum and has good resolution. Apart from that, spiral arms look relatively smooth in the infrared (Elmegreen 1981; Elmegreen & Elmegreen 1984; Block et al. 1994), drastically less affected by dust extinction, and therefore it is easier to fit them with an analytical model.

Unfortunately, not all spiral galaxies in S⁴G are suitable for the analysis with our decomposition model. The survey contains a large number of galaxies viewed at high inclination angles and, thus their structure may be significantly distorted by the projection effects. Some spiral galaxies have too faint and/or flocculent spiral structure to be reliably decomposed with our model of spiral arms.

To create a subsample of suitable spiral galaxies, we made two steps. At first, we considered a subsample of S⁴G galaxies from Díaz-García et al. (2019), which contains 391 not-highly inclined spiral galaxies, and selected only galaxies with low inclinations ($i > 40^\circ$). At the second stage, we performed visual inspection of all galaxies from the initial sample and selected objects with the most

Table 1. Some general characteristics of galaxies in our sample.

Galaxy	i deg (1)	d Mpc (2)	T (3)	AC (4)	$M(B)$ mag (5)	D_{25} arcmin (6)
ESO508–024	31.5	42.9	5.0	G	−19.3	2.1
IC0769	41.8	34.5	3.5	G	−19.3	2.2
IC1993	21.3	13.6	2.0	M	−18.2	2.8
IC2627	17.4	33.2	4.0	G	−19.9	2.4
IC4237	46.1	40.1	3.0	M	−19.8	2.1
NGC0895	44.3	27.8	5.0	M	−19.9	3.3
NGC0986	26.0	24.8	2.0	G	−20.4	4.0
NGC2460	45.7	20.7	1.0	M	−19.0	1.8
NGC3507	29.8	17.9	3.0	G	−19.2	3.0
NGC3596	21.4	20.9	4.0	M	−19.8	3.6
NGC3683A	47.8	35.3	4.0	M	−20.0	2.0
NGC3684	47.3	20.4	5.0	M	−19.2	2.3
NGC3686	35.2	20.3	4.0	M	−19.5	2.9
NGC3687	18.0	37.9	1.5	M	−19.9	1.4
NGC4067	41.9	37.4	2.0	M	−19.5	1.1
NGC4165	48.3	29.9	2.5	G	−18.1	1.2
NGC4314	20.4	17.0	1.0	G	−19.8	3.7
NGC4548	39.0	11.0	1.5	G	−19.3	5.5
NGC4680	39.3	38.3	3.0	G	−19.7	1.3
NGC4902	21.6	40.6	2.5	M	−21.2	2.7
NGC5194	32.9	8.6	4.0	G	−21.1	13.8
NGC5240	47.2	33.1	3.0	M	−18.7	1.8
NGC5247	29.8	22.5	5.0	G	−21.0	5.4
NGC5364	47.9	21.0	3.5	M	−20.4	3.8
NGC5427	25.2	39.2	4.0	G	−21.0	3.6
NGC7167	26.1	30.8	5.5	G	−19.7	1.8
NGC7661	43.2	26.3	7.5	G	−18.0	1.8
NGC7798	31.9	27.9	2.5	G	−19.2	1.4
PGC028380	46.0	38.9	8.0	G	−18.1	1.3

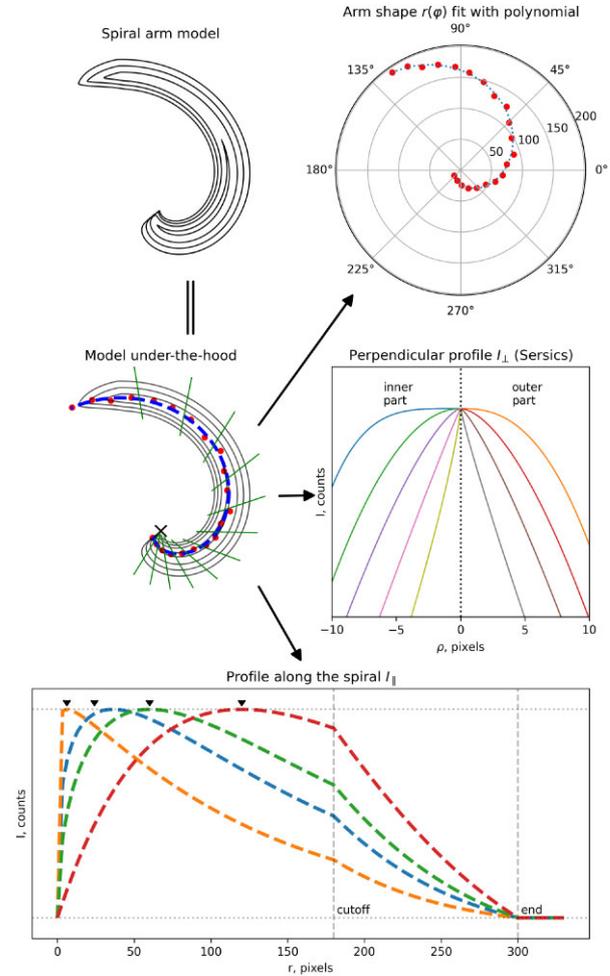
Notes. (1) Galaxy inclination from Salo et al. (2015); (2) Distance from NED, <https://ned.ipac.caltech.edu/>; (3) Hubble type from Buta et al. (2015); (4) Arm class from Buta et al. (2015): G is grand-design, M is multi-armed; (5) B -band absolute magnitude from Makarov et al. (2014), <http://leda.univ-lyon1.fr/>; (6) Optical diameter from Makarov et al. (2014)

prominent spiral structure, which resulted in a sample of 29 galaxies. These galaxies are listed in Table 1 along with some of their basic properties.

Besides galaxy images, S⁴G provides error (noise) maps, a unified PSF image, and masks for each galaxy frame (Salo et al. 2015). The PSF image has a FWHM of 1.7 arcsec. Also, we note that mask images from S⁴G only cover stellar objects and background/foreground galaxies. Different small-scale features in galaxies, such as star forming regions, were ignored. However, these sources, if left unmasked, can influence fit results, and in some cases we had to modify the initial mask to exclude such objects from our fitting.

3 SPIRAL ARMS MODEL

Below, we describe the motivation for what we expect to see in suitable spiral arm model and explain how our preferred model looks. We decide to not use symmetric models like the one presented in GALFIT (Peng et al. 2010) because the spiral arms of some galaxies are clearly asymmetric. In our model, the arms are modelled independently of each other. They are also modelled independently from the disc and are then superimposed onto the


Figure 1. Schematic representation of the used spiral arm model (see the text in Section 3 for details).

disc as a separate component, even though spiral arms are physically features which are built from the disc’s material. We consider three different meaningful properties for each spiral arm to pay attention to, namely its shape, its profile along the spiral arm, and its profile across the spiral arm. Thus, we define model parameters which are meaningful on their own and clearly represent certain arm properties.

First, we will describe the model conceptually, and then will provide the exact formulae. The model is illustrated in Fig. 1. Spiral arms in galaxies have a variable pitch angle (Savchenko & Reshetnikov 2013) and logarithmic spirals are inappropriate for describing their overall shape. We use the function $r(\varphi)$ which is the so-called shape function of the arm (Binney & Tremaine 2008, p. 471), which determines the shape of the ridge-line of the arm and therefore its overall geometry.

Since spiral arms are disc features, it is natural to assume that their intensity along the arm should decline exponentially with radius. However, to make spiral arms appear smooth, a transition segment between zero and its peak intensity must be implemented. Also, to represent the potential truncation of arms in the outer disc, a region to decrease the intensity to zero in outer parts is needed (cutoff region). Hereafter, we consider I_{\parallel} to denote relative intensity exactly along the ridge-line of spiral arm ($r(\varphi)$, φ). Such a profile is shown in the lower plot of Fig. 1, where different positions of highest intensity are

Table 2. Parameters of the spiral arm model.

Part	Parameter	Description
	X_0, Y_0^*	Coordinates of the galactic centre
	PA^*	Position angle of galactic plane
	i^*	Inclination of galactic plane
	I_{\max}	Maximum intensity in the arm
$r(\varphi)$	m_0, \dots, m_3^*	Pitch angle polynomial coefficients
	r_0, φ_0^*	Coordinates of beginning of the arm
	cw/ccw*	Arm winding direction
I_{\parallel}	φ_{\max}	Azimuthal angle of maximum intensity
	$\varphi_{\text{cutoff}}^*$	Azimuthal angle of cutoff beginning
	φ_{end}^*	Azimuthal angle of end of the arm
	h_s	Arm exponential scale
I_{\perp}	$w_e^{\text{in}}, w_e^{\text{out}}$	Half-width inwards and outwards
	$n^{\text{in}}, n^{\text{out}}$	Sérsic index inwards and outwards
	ξ	Arm width increase rate

Note: parameters marked with the asterisk were determined at the preliminary step and were fixed during the decomposition (see the text).

marked by black triangles, and the constant angles at the beginning and end of the cut-off region are shown with vertical dashed lines.

For light distribution across the arm, different models can be used. We take into account that the distribution can be asymmetric inwards and outwards, and use a Sérsic function thanks to its flexibility, with both w_e (the half-light radius for the radial direction across the spiral) and n independently fitted towards and away from the centre of the galaxy. Such behaviour is illustrated schematically in the central right plot of Fig. 1. We also note that arm width can vary along a spiral (Savchenko et al. 2020). Hereafter, we define I_{\perp} as the relative intensity along a constant φ , i.e. across the spiral arm but not perpendicularly.

Combining all the above with I_{\max} defined as the maximum intensity in the whole arm, we get the following function in intrinsic disc coordinates for total 2D intensity I in a spiral arm:

$$I(r, \varphi) = I_{\max} \times I_{\parallel}(r(\varphi), \varphi) \times I_{\perp}(r - r(\varphi), \varphi), \quad (1)$$

We now provide details about each function from equation (1). All parameters of the model and their descriptions are listed in Table 2. First, the shape function $r(\varphi)$ is defined in such a way that $\log r$ is a fourth-degree polynomial in φ :

$$r(\varphi) = r_0 \times \exp \left(\varphi \sum_{i=0}^3 m_i \left(\frac{\varphi}{2\pi} \right)^i \right). \quad (2)$$

Here, φ is counted from the angle φ_0 in the direction of spiral winding, (r_0, φ_0) is a starting point of the arm, and m_i are the corresponding polynomial coefficients.

The distribution of the surface brightness along the spiral arm is a three-term function to allow the growth of the brightness at the beginning of the arm, an exponential decrease outside of its brightness point, and a truncation at the end of the arm:

$$I_{\parallel}(r(\varphi), \varphi) = \frac{1}{\bar{I}} (h_s \varrho(\varphi))^{\varrho(\varphi_{\max})} \times e^{-\varrho(\varphi)} \times T(\varphi_{\text{cutoff}}, \varphi_{\text{end}}), \quad (3)$$

where \bar{I} is a normalization constant, h_s is the scale of exponential decay, $\varrho = (r(\varphi) - r_0)/h_s$ is a relative distance to the origin of the arm, φ_{\max} is the value of the polar angle where the maximum surface brightness I_{\max} is reached. The truncation function

$$T(\varphi_{\text{cutoff}}, \varphi_{\text{end}}) = 1 - \Theta(\varphi - \varphi_{\text{cutoff}}) \frac{\varphi - \varphi_{\text{cutoff}}}{\varphi_{\text{end}} - \varphi_{\text{cutoff}}} \quad (4)$$

depends on the value of the angle φ_{cutoff} , where the profile cutoff begins, and φ_{end} , where and after which the intensity is set to zero. Θ is the Heaviside function. Note that, we wrote equations for intensity as a function of radius. The same is true for I_{\parallel} plot in Fig. 1. Radius itself is a function of azimuthal angle and azimuthal angle is used as a model parameter to set borders for both exponential and linear growth. It is more convenient to do it in this way because it allows us to use the exponential scale h_s for the spiral in the same way that h is used for the exponential disc.

A surface brightness distribution across the arm is modelled by a couple of Sérsic functions to fit the inside (closer to the galaxy centre) and the outside (farther from the galaxy centre) parts of the arm, as demonstrated in Fig. 1. Both functions have an additional common parameter, that governs how their widths changes along the arm to allow a spiral pattern with variable width:

$$I_{\perp}^{\text{in/out}}(\rho, \varphi) = \exp \left(-b_n^{\text{in/out}} \times \left(\frac{\rho}{\sqrt{(w_e^{\text{in/out}})^2 + (\varphi \times \xi)^3}} \right)^{\frac{1}{n^{\text{in/out}}}} \right), \quad (5)$$

where upper indexes ‘in’ and ‘out’ stand for the inner and outer parts of the arm. Here, $\rho = r(\varphi) - r$ is the radial distance to the ridge of the arm, n is the Sérsic index, w_e is the half-width of the spiral, the coefficient ξ describes the widening of the arm towards the outer edge of the galaxy, and b_n is not a free parameter, but a normalization coefficient of the Sérsic law.

Some notable features of our model are

(i) each spiral arm can be fitted individually (no imposed symmetry around the centre, and an arbitrary number of spiral arms can be included in the model)

(ii) The major advantage of the described model is that almost all parameters have a clear geometrical/physical meaning. Although this number of parameters seems to be large, it is necessary to make the model flexible enough to reproduce various shapes and properties of spiral arms. For example, the model of spiral arms in Peng et al. (2010) contains up to 103 parameters which mostly have no physical meaning by themselves. On the contrary, in Lingard et al. (2020), a very simple model of 6 parameters was used. In particular, their model produces spiral arms with a constant pitch angle which is a crude approximation for real galaxies, especially in their periphery (Savchenko & Reshetnikov 2013; Savchenko et al. 2020).

(iii) the pitch angle μ_{φ} at a certain point on the arm with azimuthal angle φ can be calculated as follows:

$$\mu_{\varphi} = \arctan \left(\sum_{i=0}^3 (i+1) m_i \left(\frac{\varphi}{2\pi} \right)^i \right). \quad (6)$$

(iv) The average pitch angle (μ) for any part of the arm (for example, in the range $[\varphi_1, \varphi_2]$) can be found as the arctangent of the slope coefficient of the linear fit of the points of the spiral structure in the log-polar coordinates, i.e. $\log r(\varphi_2)/r(\varphi_1) = \tan(\mu) \times (\varphi_2 - \varphi_1)$.

The centre point (X_0, Y_0), inclination i , and positional angle PA are also amidst the parameters of the model and correspond to the position and orientation of the galaxy as a whole. The centre point and inclination are usually the same for all components (disc, bulge, spirals).

The flexibility that comes with this model has its price. Bad initial estimations for parameters can lead to a long convergence, and the stability of the result is also unclear. It is a planar 2D model used for a 2D decomposition, so lacks a proper account for the intrinsic extinction or galaxy thickness (see the discussion about the

difference between 2D and 3D decomposition in Mosenkov et al. (2015). Finally, there is no physical motivation for certain properties of the selected model, such as whether or not the brightness should follow an exponential law. This is mostly because we lack a priori information about an isophote's behaviour in real spiral arms. This and consequent studies should help to acquire this knowledge as well.

4 DECOMPOSITITON AND VALIDATION

For decomposition of our galaxy images, we employ the IMFIT package (Erwin 2015) which is flexible enough to add new user-defined classes and to use different optimization techniques. We modified the latest IMFIT version 1.9 to implement our spiral arm model function¹, described in detail Section 3.

The main difficulty of using a complex model with a big number of degrees of freedom is finding proper initial values of the free parameters. If initial values are not close enough to their optimal values, the optimization iteration process can converge to one of possible local minima or even to singular points of the function used (one or more parameters can become equal to zero or infinity). Moreover, fitting of a large number of parameters is a time-consuming procedure and finding an appropriate initial guess becomes even more important. An additional problem is to find a proper combination of model components, which better suits a particular galaxy, because galaxies can have a different set of structures (for example, a bar, a lens, an active nucleus may, or may not appear in a galaxy).

At a first step, we perform a decomposition using a model without spiral arms, in order to use its results as initial conditions for a more complicated model with spiral arms. As a starting point for this decomposition, we use results from Salo et al. (2015), where such a decomposition was performed using the GALFIT code (Peng et al. 2002). For each galaxy in our sample, we converted their results into an IMFIT input file and then performed IMFIT fitting. In some cases, we had to adopt a different set of components, e.g. an exponential disc + point source model instead of an exponential disc + Sérsic bulge model (in case the bulge size is too small for a proper fitting), or adopt a more complex structure by adding new components.

To simplify our fitting, we obtained some spiral arm parameters separately and fixed them, namely parameters which define position, shape and length of spiral arms. To determine these parameters, we traced the spiral arms by manually placing points in SAOIMAGEDS9² package (Joye & Mandel 2003) along the arms ridges and then saved their coordinates. Our PYTHON script used these coordinates for estimating initial guess values and then performed approximation of the shape of the spiral arms by means of our model. The initial guess for the remaining parameters of the spiral arm model was chosen manually and fitted by Levenberg–Marquardt algorithm (Moré 1978) which is one of the fitting methods implemented in IMFIT. Since the initial guess and bounds of parameters were not always good, we usually had to perform fitting multiple times, especially for the models with spiral arms. We estimated the goodness of fit by visual inspection of the real images and their models, as well as the corresponding residual images and azimuthally averaged surface brightness profile. Adding spirals to our fit model resulted in a considerably longer computational process, typically 1–2 orders of magnitude longer as compared to a simple fit with a standard set of

¹This new class incorporated in IMFIT can be found at https://github.com/IVChugunov/IMFIT_spirals.

²<https://sites.google.com/cfa.harvard.edu/saoimageds9>

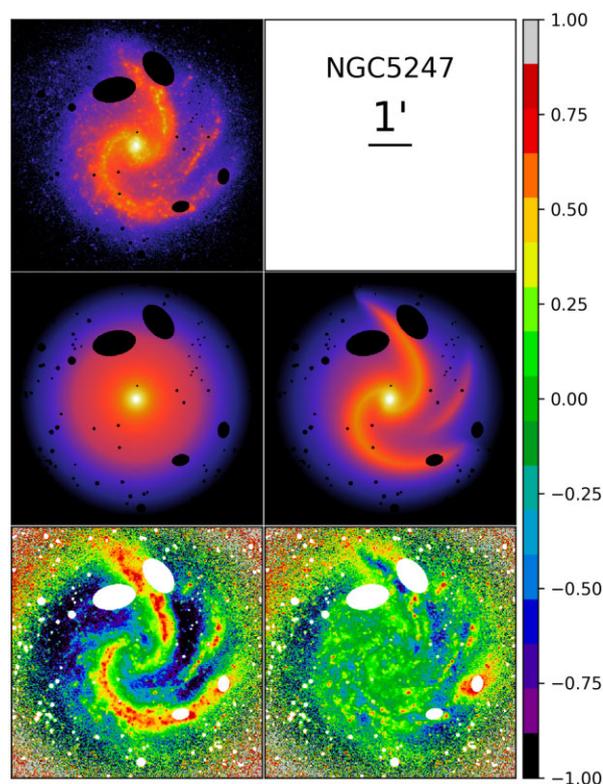


Figure 2. Decomposition of NGC 5247 shown as an example. From top to bottom: original image, models, and relative residuals. The classical model and the corresponding residual image are on the left column, model with spiral arms and corresponding residual are on the right column. Relative residual images are defined as the difference between the image and model fluxes, divided by the image flux. This value is dimensionless, and numerical values on the colourbar on the right correspond to the relative residual. Large positive and negative values of the relative residual depict under- and overestimated brightnesses in the model image, respectively, whereas zero means good agreement.

bulge and disc components. On average, fitting of a single model without spiral arms required computational time of about tens of seconds with Intel Core i5-7200U CPU. When spiral arms were added to the model, the time were from a few minutes up to an hour. As mentioned above, to obtain a final model of a single galaxy it was usually needed to perform fitting several times, increasing the required time even more.

At the end we obtained two models for each galaxy: the first one consists of only axially symmetric components without spiral arms, hereafter ‘classical model’, and the other model contains, besides the same set of components, an appropriate number of well-visible spiral arms. This approach allows us to compare these models with each other and to estimate biases in the measured parameters if spirals are not included into the model. In Fig. 2, we show an example of decomposition for NGC 5247. Decomposition results for all galaxies, including model parameters and images, are available online; example for one galaxy is shown in Appendix A (Fig.). Large inconsistencies between the classical model and the input galaxy image are clearly seen on the residual image, whereas the model with spiral arms has much more resemblance with the original galaxy image.

In order to validate our results, we perform some checks. First, we measure the χ^2 statistic for both models of each galaxy. Models with spiral arms all have better χ^2 values than classical models, as seen in

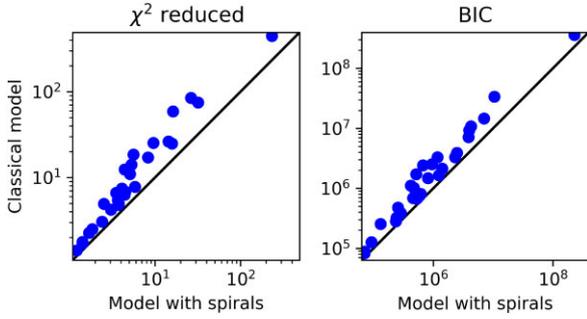


Figure 3. χ^2 (left) and BIC (right) statistic values. Each dot marks corresponding value for two models of galaxy: model with spirals (x -axis) and classical one (y -axis). We note that chi-square statistic (χ_v^2) values seems unrealistically large, with the highest value $\chi_v^2 > 200$ even for a model with spiral arms of M 51 (NGC 5194). However, Salo et al. (2015) also obtained χ_v^2 values much higher than unity for some galaxies using exactly the same images and error maps as we used in this study. For example, the bulge + disc decomposition model of M 51 in Salo et al. (2015) has $\chi_v^2 \approx 1600$.

Fig. 3. However, models with a greater number of fitting parameters should generally have better χ^2 value, and to account for this, we use BIC (Bayesian Information Criterion; Bailer-Jones 2017) statistics. BIC considers not only the difference between a model and an image, but also the complexity of the model, giving a penalty for a greater number of parameters. Again, in Fig. 3, one can see that the BIC values also improve for models with spiral arms. This proves that adding spiral arms to our models is justified and does not cause the overfitting problem.

We can compare our results for classical models with those from Salo et al. (2015), which, in some extent, served as a source (or as a reference, at least) of the initial guess for our models. For some galaxies, we adopted a different set of components (usually more detailed) than the authors of the aforementioned work. Nevertheless, we expect that the general parameters, such as the disc scale length or bulge-to-total ratio, should remain the same. The comparison of several parameters is shown in Fig. 4. For some parameters (the Sérsic index n for bulges and B/T), we see only a rough correspondence with a large scatter at best. Possibly, bulges in our sample are faint and the addition of different components changes their parameters significantly, in agreement with Läsker, Ferrarese & van de Ven (2014). At the same time, there is a good agreement for other parameters, such as the disc scale length h , bulge effective radius r_e^{bulge} , and bar effective length r_e^{bar} . Interestingly, we notice that bars in Salo et al. (2015) are systematically stronger than those in our work. Perhaps, this can be attributed to the fact that for most galaxies in our sample we used generalized Sérsic ellipses instead of a Ferrers function, or due to the inclusion of other components.

The images in the $3.6 \mu\text{m}$ band show not only the distribution of the old stellar population, but also an emission of the hot dust and PAH molecules, which are mostly associated with ongoing star formation (Meidt et al. 2012). Therefore, the light distribution in a $3.6 \mu\text{m}$ band image of a spiral galaxy cannot be directly connected to the stellar mass distribution. For this reason, Querejeta et al. (2015) decomposed the original S⁴G images into stellar and non-stellar components based on the [3.6]–[4.5] colour distribution. It is of particular interest to examine how the decomposition results will change if we consider pure stellar images from Querejeta et al. (2015) instead of the original $3.6 \mu\text{m}$ band images. Unfortunately, not all galaxies in our sample were decomposed by Querejeta et al. (2015) into stellar and non-stellar components (separation is not done for IC

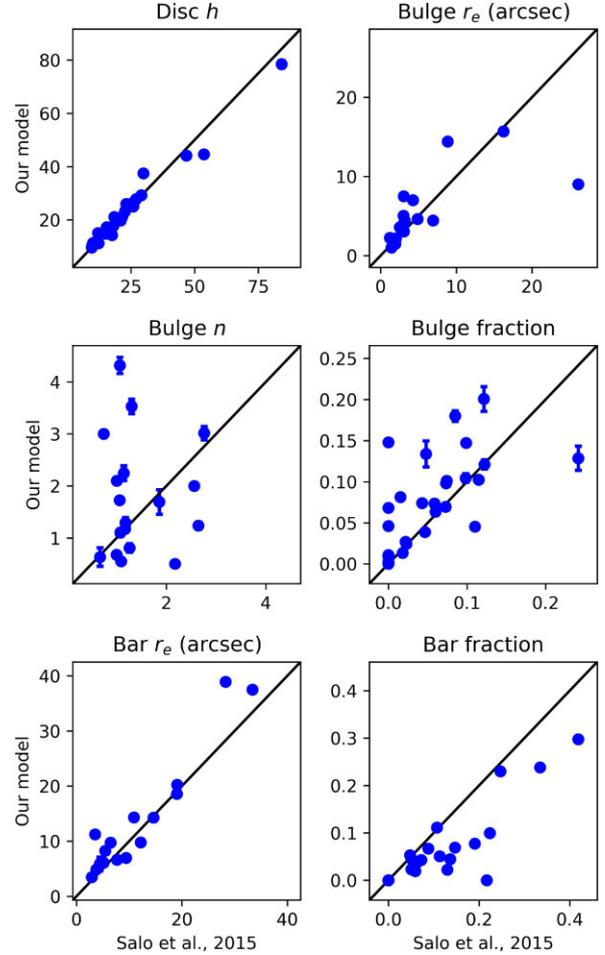


Figure 4. Comparison of different fit parameters derived for each galaxy between Salo et al. (2015) and classical models obtained in this study.

769, NGC 2460, NGC 3683A, NGC 3687, NGC 4067, NGC 4165, NGC 4314, NGC 4902, NGC 5240, NGC 7661, and PGC 28380), and some demonstrate the absence or very weak spiral structure in their stellar images (the best examples are IC 1993 and IC 4237). To measure the effect of the presence of dust and PAH emission on the retrieved parameters, we decided to perform decomposition of the stellar images for 5 galaxies in the same way as was done for the original images. The selected galaxies, namely IC 2627, NGC 895, NGC 3686, NGC 4680, and NGC 5247, demonstrate a fittable well-defined spiral structure on their stellar images. For these galaxies, we find a significant difference between the spiral arm parameters fitted utilizing the original and dust-subtracted images, which we discuss in Section 6.6.

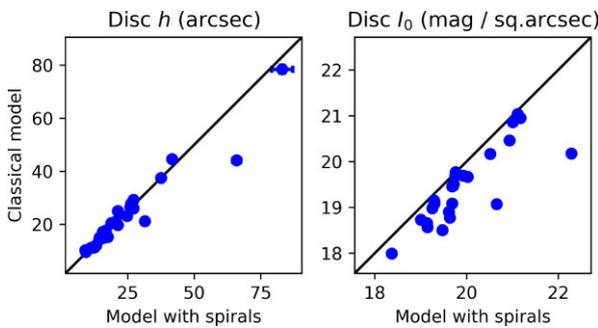
5 THE EFFECTS OF INCLUSION OF SPIRAL ARMS ON THE MODEL COMPONENTS

To show the influence of the spiral pattern on the results of decomposition, we compared the parameters of the components in our classical models and models with spiral arms. The difference between them can be interpreted as a systematic error of the parameters estimation of classical decomposition. A comparison of the disc and bulge parameters between the classical models and models with spiral arms is shown in Table 3.

Table 3. Difference of the parameters between classical models and models with spiral arms.

Galaxy	Disc				Bulge				Bar				Components
	h^c/h^{SP}	I_0^c/I_0^{SP}	r_c^c/r_c^{SP}	I_c^c/I_c^{SP}	n^{SP}	n^c	$(B/T)^{SP}$	$(B/T)^c$	r_c^c/r_c^{SP}	I_c^c/I_c^{SP}	$(Bar/T)^{SP}$	$(Bar/T)^c$	
ESO508–024	0.96	1.23	1.00	0.44	0.52	0.72	0.03	0.01	1.50	0.49	0.08	0.11	DBbar
IC0769	1.03	1.38	–	–	–	–	0.00	0.00	0.68	1.76	0.11	0.07	DBbar
IC1993	1.18	1.05	0.68	1.89	1.81	1.10	0.04	0.02	–	–	–	–	DB
IC2627	1.06	1.23	0.87	1.20	1.54	1.29	0.08	0.06	–	–	–	–	DB
IC4237	1.00	1.14	–	–	–	–	0.01	0.01	1.00	1.00	0.04	0.05	DBbarRL
NGC0895	1.06	1.39	1.00	0.95	0.91	1.00	0.06	0.07	–	–	–	–	DB
NGC0986	1.00	1.55	1.54	0.39	1.05	2.25	0.16	0.20	1.00	0.94	0.26	0.24	DBbarR
NGC2460	–	–	0.88	1.38	4.90	4.32	0.12	0.13	–	–	–	–	DB
NGC3507	1.07	1.22	0.61	2.69	4.76	3.02	0.10	0.07	1.12	0.84	0.06	0.05	DBbar
NGC3596	0.67	4.32	0.41	1.79	1.22	1.24	0.22	0.07	–	–	–	–	DB
NGC3683A	1.01	1.29	–	–	–	–	0.00	0.00	0.67	1.32	0.04	0.02	DBbar
NGC3684	0.87	1.55	3.73	0.10	0.61	3.53	0.03	0.08	0.84	0.58	0.10	0.02	DBbar
NGC3686	1.02	1.19	0.90	1.27	2.22	1.69	0.03	0.03	1.05	0.95	0.03	0.02	DBbar
NGC3687	0.92	1.74	0.67	2.67	3.23	1.17	0.15	0.10	1.06	0.72	0.07	0.05	DBbar
NGC4067	1.14	1.29	1.00	0.76	2.69	3.00	0.17	0.13	0.94	1.10	0.10	0.10	DBbar
NGC4165	1.00	1.24	0.73	1.35	1.04	0.63	0.06	0.04	–	–	–	–	DB
NGC4314	0.67	6.98	0.80	1.36	1.10	0.55	0.14	0.10	1.00	0.84	0.30	0.30	DBbarRL
NGC4548	–	–	0.97	1.10	2.42	2.00	0.15	0.15	1.08	0.86	0.22	0.23	DBbar
NGC4680	0.91	1.71	–	–	–	–	0.05	0.05	0.93	0.85	0.08	0.04	DBbar
NGC4902	0.93	2.21	0.82	1.11	0.91	0.81	0.10	0.07	1.00	1.09	0.10	0.07	DBbar
NGC5194	0.94	2.44	0.70	1.41	1.07	0.67	0.23	0.12	–	–	–	–	DB
NGC5240	1.10	1.25	0.45	3.61	1.15	0.50	0.02	0.01	–	–	–	–	DB
NGC5247	–	–	1.34	0.60	1.29	1.72	0.12	0.18	–	–	–	–	DB
NGC5364	1.07	1.24	1.11	0.59	1.37	2.10	0.05	0.05	–	–	–	–	DB
NGC5427	0.93	1.92	0.79	1.48	0.50	0.50	0.11	0.10	–	–	–	–	DB
NGC7167	1.04	0.99	1.73	0.91	3.17	1.84	0.09	0.15	–	–	–	–	DB
NGC7661	1.09	1.07	–	–	–	–	–	–	0.90	1.06	0.06	0.04	Dbar
NGC7798	1.04	1.42	–	–	–	–	0.11	0.10	1.00	1.26	0.07	0.04	DBbar
PGC028380	0.94	1.15	–	–	–	–	–	–	1.03	0.90	0.08	0.08	Dbar

Notes: index ^c stands for ‘classical’ model parameter, ^{SP} stands for a model with spiral arms. Letter combination in ‘Components’ describes the set of components except spiral arms which were used to fit each galaxy: D–disc, B–bulge, bar–bar, R–ring, and L–lens. Different functions were used to fit these galaxy components. For example, exponential or broken exponential functions were used to fit the disc, and a point source function was sometimes used for the bulge when it was too small to be resolved. Dashes in the table indicate that the corresponding parameter is undefined for this galaxy, as in the case of broken exponential discs in NGC 2460, NGC 4548, and NGC 5247, or bulges modelled as a point source (only B/T was determined in such cases), or the corresponding component does not present in the galaxy.


Figure 5. Difference of the disc parameters between classical models and models with spiral arms. The radial scale length h is shown on the left, the central surface brightness I_0 is displayed on the right.

5.1 The disc parameters

The central surface brightness of discs (I_0) appears to be higher in classical models than in models with spiral arms, see Fig. 5 and Table 3. This is expected because the spiral arms are disc features, and if they are included, they take some part of the disc light. The mean difference for our sample is 0.5 mag. The radial scale of discs in our sample (h) does not change systematically between the classical

models and models with spiral arms, so the difference for individual galaxies is small. When spiral arms are added to the model, h may increase or decrease, but this change does not exceed 10 per cent in most of the cases.

Gao & Ho (2017) found that the radial scale length of the disc increases when spiral arms are added to the model, reasoning that spiral arms have a truncation at large radii. Following this, when one uses a pure disc model to fit a disc with spiral arms, the disc scale length becomes smaller than its actual value to account for this truncation. However, spiral arms usually do not emerge from the centres of galaxies, so spiral structure should have a brightness drop in the center which should compensate to a some extent the effect of outer truncation. Gao & Ho (2017) used a spiral arms model from GALFIT (Peng et al. 2010) (which actually represents an azimuthally distorted disc) separately from the axisymmetric disc component. This means that their model of spiral structure does not have a drop of surface brightness in the centre. In other words, their model of spiral arms has an excess of light distribution in the centre, so the disc model in this central region is underestimated which makes the axisymmetric disc profile less steep. Another decomposition with a simple model of spiral arms was carried out in Lingard et al. (2020). For disc size and ellipticity, they did not find any significant difference between their models with spiral arms and without them.

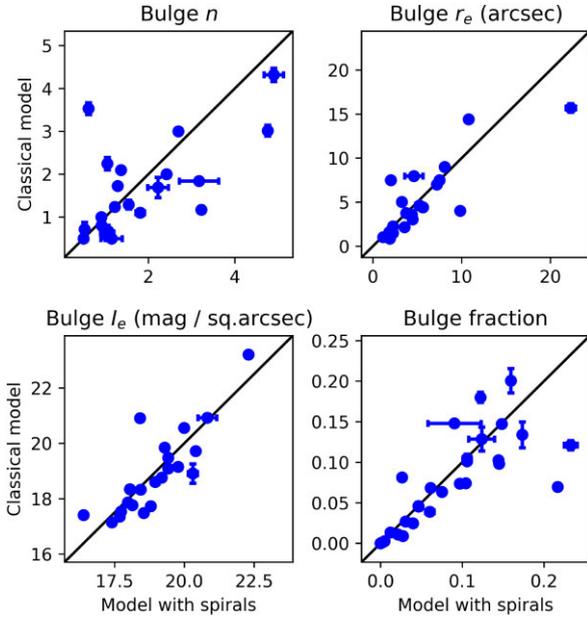


Figure 6. Difference of the bulge parameters between classical models and models with spiral arms. Upper left: Sérsic index n ; upper right: effective radius r_e^{bulge} ; lower left: effective surface brightness I_e^{bulge} ; lower right: bulge-to-total luminosity ratio.

5.2 The bulge parameters

The systematic difference of the bulge parameters (effective radius r_e^{bulge} , effective surface brightness I_e^{bulge} , Sérsic index n , or bulge-to-total luminosity ratio B/T) between our classical models and models with spiral arms is noticeable only for the sample as a whole (see Fig. 6 and Table 3). When spiral arms are added, the mean changes of parameters are the following: r_e^{bulge} increases by 20 per cent, I_e^{bulge} decreases by 5 per cent, n increases by 26 per cent and B/T increases by 33 per cent. However, the scatter around these values is large for individual galaxies. For example, the B/T and n parameters can increase or decrease by factor of 2 when spiral arms added to the model. The explanation of the average trend in the models is as follows. When spiral arms are included in the model, the measured central surface brightness of the disc becomes lower. The spiral arms are not present in the center, so the decrease of the surface brightness in the centre should be compensated by some other components, such as the bar or the bulge. The shape of the distribution of the ‘remaining’ luminosity density, to be fitted with the bulge and other components, changes and the parameters of these components may be different. The brightness in the very center of the bulge does not change much because in this point it is already much higher than disc brightness. In the same time, extended ‘wings’ may appear in the outer parts of a bulge which require an increased n . Overall, the bulge becomes more extended and more luminous, which leads to the increase of r_e^{bulge} and B/T . The decrease of I_e^{bulge} may seem to contradict to these reasons, but, as the bulge becomes more extended, its half-light radius shifts to the outer fainter parts, which leads to the decrease of I_e^{bulge} , while the central brightness of the bulge remains nearly constant with an increased n .

Therefore, we conclude that neglecting spiral arms in decomposition may lead to significant errors and biases in the estimated bulge parameters for individual galaxies. Gao & Ho (2017) reported that adding spiral arms in their model changes the bulge parameters insignificantly; however, their sample contained only

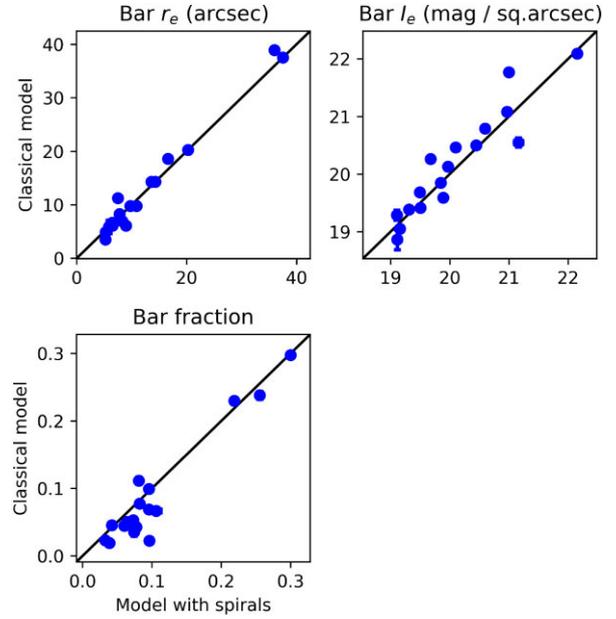


Figure 7. Difference of bar parameters between classical models and models with spiral arms. Upper left: effective radius r_e^{bar} ; upper right: effective surface brightness I_e^{bar} ; lower left: bar-to-total luminosity ratio.

6 spiral galaxies which seems to be not enough to draw robust statistical conclusions considering the large scatter in our results. As discussed in Section 5.1, we can explain this discrepancy by the fact that the spiral arms model in Gao & Ho (2017) does not have a drop of surface brightness in the center. When spiral arms are added to the model, the decrease of the central surface brightness of the disc is compensated by the model of spiral arms. Therefore, the ‘remaining’ surface brightness, which is fitted by a bulge, remains the same as in the model without spirals, and the bulge parameters are not expected to change. Sonnenfeld (2022) performed a Sérsic profile fitting for artificial images of galaxies with spiral arms and found that the half-light radius of galaxy and the total flux is overestimated by 30 and 15 per cent, respectively, for the spiral structure contributing 10 per cent of total light but for disc-dominated galaxies this bias is much smaller. In our sample, galaxies have small B/T and are disc-dominated. Lingard et al. (2020) found that the bulge-to-total ratio is higher in their models with spiral arms than in simple Sérsic bulge + exponential disc models.

5.3 The bar parameters

Among 29 galaxies from our sample, 17 are barred, so the effects from inclusion of spiral arms on the bar parameters are also interesting to investigate. In Fig. 7 and Table 3, we present a comparison for the bar size (expressed in terms of the effective radius along the major axis r_e^{bar}), bar effective surface brightness I_e^{bar} , and bar-to-total luminosity ratio Bar/T . When spiral arms are added to the model, the mean r_e^{bar} increases by 5 per cent, the mean Bar/T increases by 49 per cent with the most significant changes occur when Bar/T is small, and the mean I_e^{bar} increases by 7 per cent. Just as for bulge parameters, the scatter is large. Therefore, Bar/T increases stronger than the B/T when spiral arms are added but the change of r_e^{bar} is smaller than the change of r_e^{bulge} .

We suggest that such a difference may be caused by the fact that the bulges in our sample are small, concentrated, and have extended

Table 4. Parameters of the spiral arms in our sample galaxies.

Galaxy	S/T (1)	$\langle h_s \rangle/h$ (2)	$\langle w \rangle/h$ (3)	σ_w/w (4)	$\langle A \rangle$ (5)	$\langle \mu \rangle$ deg (6)	σ_μ deg (7)	$\langle \Delta \mu \rangle$ deg (8)	N_{arms} (9)
ESO508-024	0.08	0.09	0.24	0.02	0.23	18.4	1.6	5.6	2
IC0769	0.21	1.47	0.52	0.02	0.00	13.9	0.4	2.4	2
IC1993	0.21	0.86	0.46	0.25	0.43	11.9	0.8	8.3	3
IC2627	0.24	2.74	0.64	0.50	-0.04	28.0	9.2	12.8	3
IC4237	0.25	3.61	0.52	0.24	0.25	12.9	5.2	2.1	3
NGC0895	0.25	2.28	0.29	0.02	-0.30	18.4	0.5	6.7	2
NGC0986	0.18	0.34	0.52	0.09	-0.48	13.9	1.4	18.4	2
NGC2460	0.29	-	-	0.76	-0.21	11.0	12.0	7.6	5
NGC3507	0.21	0.68	0.57	0.12	-0.02	10.6	1.3	5.9	2
NGC3596	0.39	0.26	0.44	0.12	0.17	14.0	2.8	5.1	2
NGC3683A	0.16	1.88	0.54	0.60	-0.20	17.5	4.2	8.6	4
NGC3684	0.14	0.64	0.50	0.27	-0.13	24.3	9.7	9.0	3
NGC3686	0.18	1.07	0.55	0.20	0.02	18.2	6.9	5.2	2
NGC3687	0.22	0.77	0.75	0.56	-0.16	11.3	4.6	6.9	3
NGC4067	0.20	1.68	0.80	0.28	-0.18	8.6	6.6	9.2	3
NGC4165	0.17	0.89	0.61	0.01	-0.12	11.2	2.8	4.7	2
NGC4314	0.14	0.31	0.78	0.02	-0.27	8.0	1.2	21.3	2
NGC4548	0.14	-	-	0.48	-0.21	13.0	8.1	15.1	4
NGC4680	0.27	0.80	0.41	0.25	-0.16	15.6	3.4	8.4	2
NGC4902	0.38	0.61	0.66	0.15	-0.37	14.9	5.4	2.9	3
NGC5194	0.46	0.41	0.52	0.14	-0.21	15.2	0.5	4.4	2
NGC5240	0.24	1.29	0.45	0.22	0.31	25.4	4.5	9.1	3
NGC5247	0.32	-	-	0.10	-0.30	29.4	5.3	5.4	3
NGC5364	0.26	0.94	0.45	0.13	0.14	11.8	2.5	5.4	2
NGC5427	0.36	1.02	0.48	0.39	-0.42	20.3	6.5	7.4	4
NGC7167	0.13	0.77	0.34	0.01	-0.30	21.0	2.5	9.8	2
NGC7661	0.14	3.45	1.18	0.14	-0.12	27.8	4.2	12.3	2
NGC7798	0.19	3.73	0.33	0.41	0.60	11.0	7.7	4.8	3
PGC028380	0.12	7.58	0.55	0.29	0.65	21.5	1.2	6.8	2

Note. (1) Spiral-to-total ratio; (2) Mean spiral arm exponential scale relative to the disc exponential scale; (3) Mean spiral arm width relative to the disc exponential scale; (4) Standard deviation of the spiral arm width relative to its mean value; (5) Mean asymmetry of the spiral arms; (6) Mean pitch angle of the spiral arms; (7) Standard deviation of averaged pitch angles of arms in galaxy; (8) Average value of variations ($\Delta \mu$, see Section 6.2) in individual arms of galaxy; (9) Number of spiral arms

‘wings’ on their surface brightness profiles (a high Sérsic index n), while the bars usually are larger and have flatter brightness profiles (since n is usually smaller than 1 for them) and lower effective surface brightnesses. This means that a slight variation of the disc brightness in our models, caused by the inclusion of spiral arms, affects the bar and bulge parameters differently. For bulges, the mentioned variation affects primarily the faint ‘wings’, and the best-fitting bulge model turns out to have a much brighter (or fainter) periphery. This means that n changes significantly, and other parameters are also changed to retain the surface brightness in the central part. Bars, conversely, usually have well-defined borders, and their general shape remains the same. However, even a small increase of the disc brightness can decrease the overall bar luminosity substantially due to the bar large size and surface brightness lower than the bulge has. The bar effective surface brightness also varies significantly, in consistency with this interpretation.

6 SPIRAL ARMS PARAMETERS

From our decomposition, we have obtained a parametric description of the galaxies from our sample. We can now determine different properties of the spiral arms, including their width, pitch angle, and how these parameters vary with radius.

6.1 The fraction of the spiral arms in the total galaxy luminosity

We first inspect the relative fraction of the spiral arms in the total galaxy luminosity (S/T) and the bulge fraction (B/T) from our models versus Hubble types adopted from Buta et al. (2015). For most galaxies in our sample, S/T is found between 10 and 25 per cent. However, in exceptional cases, the fraction of spiral arms may exceed 45 per cent, as seen in Table 4. The highest value of S/T is achieved for intermediate-type spirals, see Fig. 8, and B/T is higher in early-type spirals, as expected. However, intermediate-type spirals with a low S/T are also present. We note that early-type spiral galaxies are located near the Hubble stage $T = 0$ which marks a transition to lenticular galaxies without spiral arms. Early-type spirals tend to have a low-gas mass fraction and low-star formation rate, and therefore they cannot have luminous starforming spiral arms (Roberts & Haynes 1994). Very late-type spirals, located near the transition to irregular galaxies, also lack an ordered, well-defined spiral structure. Such galaxies tend to have multiple flocculent arms, which are hard to fit with our model, and are often blended with the disc component. Savchenko et al. (2020) found that the fraction of spiral structure is higher in Sc-type galaxies than in Sa-type ones, in agreement with our result, and the similar overall values of S/T .

In Fig. 9, we display correlations between S/T and B/T and between S/T and disc absolute magnitude. For both types of spirals, grand-

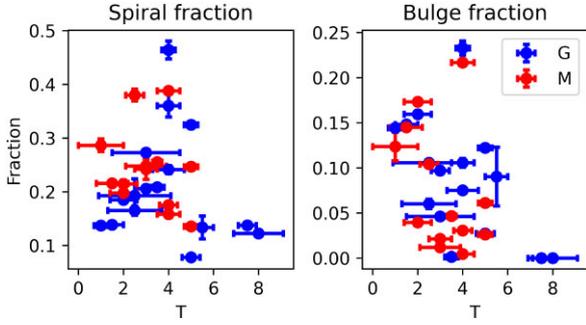


Figure 8. Relation between the Hubble type (from Buta et al. 2015) and the fraction of spiral arms. Hereafter, G stands for galaxies with grand-design spiral structure, M denotes multi-armed spirals.

design and multi-armed, S/T is higher in galaxies with a higher B/T . The same relation between S/T and B/T was found in Bittner et al. (2017) for galaxies with a low B/T , and the galaxies in our study have low B/T compared to the sample in the mentioned work. For grand-design galaxies, we also find that S/T is higher in galaxies having more luminous discs. This finding matches the fact that irregular galaxies have faint discs and, at the same time, demonstrate no clear spiral structure.

6.2 Pitch angles

Our method allows us to measure not only pitch angles of individual spiral arms, but also their variations along a single arm. In contrast, widely used Fourier-based methods provide only the pitch angle averaged over the entire galaxy. In Table 4, we show the following values: the average pitch angle for each galaxy (μ), standard deviation of the averaged individual pitch angles for all arms σ_μ , and the average value of pitch angle variations in the galaxy arms ($\langle \Delta\mu \rangle$). Defined this way, σ_μ describes the difference between all spiral

arms in a galaxy and has no connection to the measurement errors, whereas $\langle \Delta\mu \rangle$ for a single arm describes the average variability of the pitch angles, or, in other words, how far the shape of the arm from the logarithmic spiral is. For an individual arm, the variability is computed in the following way: pitch angles are measured at five uniformly placed points along a spiral arm (using equation 6), and the standard deviation of values in this sample is $\Delta\mu$ for this arm. For example, galaxies NGC 986 and NGC 4314 have small σ_μ but large $\Delta\mu$. Indeed, both galaxies have two very symmetric arms, albeit their shapes are far from logarithmic spirals with constant pitch angles. Instead, they form pseudorings and their pitch angles turn negative at some point, which means that in some range along the arm the distance from the galaxy centre to a point on the arm decreases (see on-line materials).

Both σ_μ and $\langle \Delta\mu \rangle$ are far from zero in many cases. In our sample, the average value of σ_μ is 4.2° and it is 8.0° for $\langle \Delta\mu \rangle$. In some cases, σ_μ/μ exceeds $1/2$. In other words, the pitch angles of spiral arms in a single galaxy may vary significantly and the average value of pitch angle is not sufficient to characterize the galaxy spiral structure. Moreover, even the averaged values of individual spiral arms do not seem to be a reliable measure because spiral arms usually have variable pitch angles, in agreement with Lingard et al. (2021) and again with Savchenko & Reshetnikov (2013).

We confirm a strong relationship between the spiral arm pitch angle and the Hubble type of a galaxy (Fig. 10). This is a well-established relation which has been reported since Kennicutt (1981) because the spiral arms' pitch angle is one of the criteria of the Hubble classification, and this result also validates our method. Fig. 13 in Savchenko et al. (2020) shows a correlation between pitch angle and Hubble type based on results from different studies. Although the general trend does exist, the scatter of this correlation is very large, which is also seen in Díaz-García et al. (2019). The scatter of our correlation in Fig. 10 is less pronounced, perhaps due to the more accurate estimation of the pitch angle thanks to our sophisticated modelling of the galaxy structure.

Spiral fraction correlations

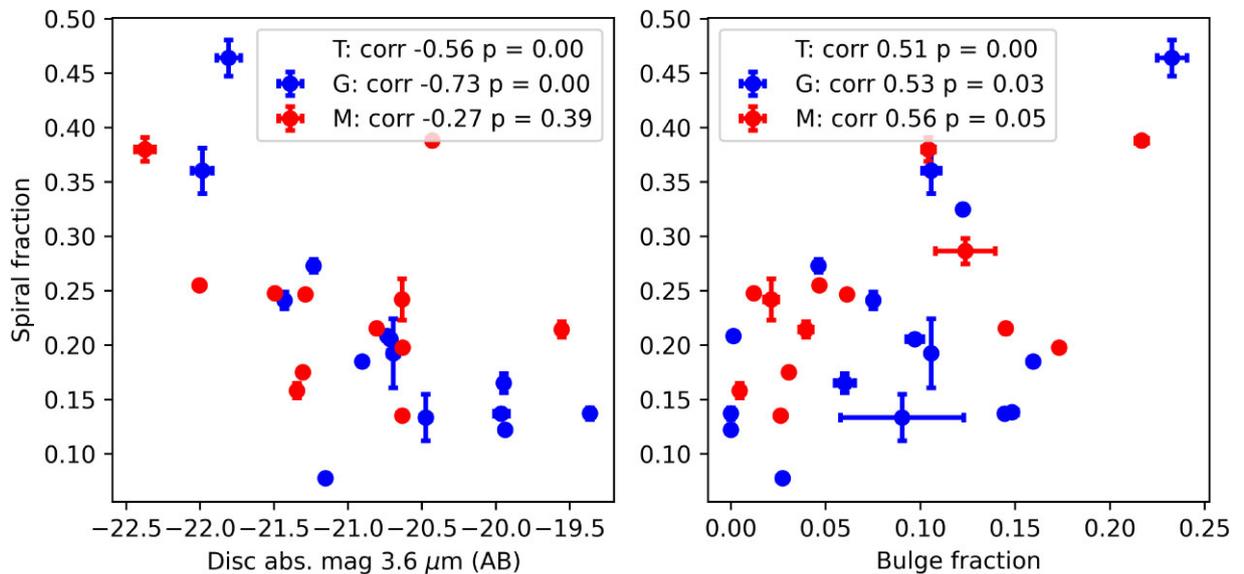


Figure 9. Correlations between S/T and disc absolute magnitude in $3.6 \mu\text{m}$ in AB system (left) and between S/T and B/T (right). Hereafter, in the plot legend ‘corr’ denotes Pearson correlation coefficient and ‘p’ is the p-value. These numbers are indicated for the total sample (marked with T), and separately for sub-samples of grand-design (G) and multi-armed (M) galaxies.

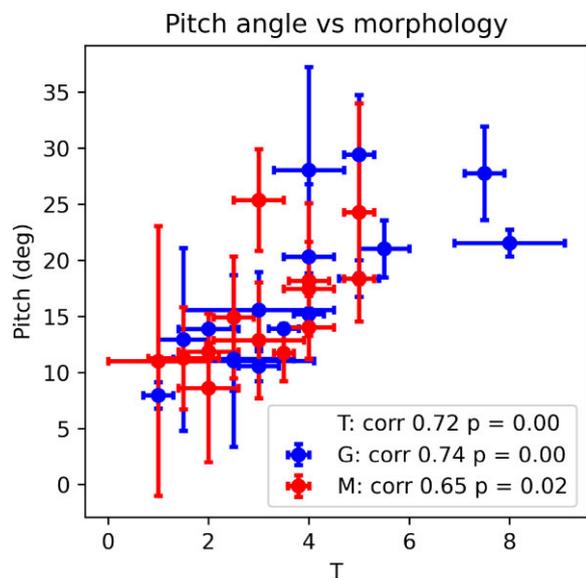


Figure 10. Dependence of the mean pitch angle on morphological type. G – grand-design galaxies, M – multi-armed.

For pitch angles, we do not find any significant correlation with S/T , see Fig. 11. There are some theoretical studies considering a dependence between these quantities. For example, Hamilton (2023) predicts a positive correlation between the amplitude of spiral structure and its pitch angle. However, Pérez-Villegas, Pichardo & Moreno (2015) predict a negative correlation between spiral arm mass and pitch angle. Observations show a negative correlation between these parameters (Díaz-García et al. 2019).

We find a weak anticorrelation between pitch angle and B/T , see Fig. 11. In other words, galaxies with more prominent bulges have more tightly wound spiral arms. This is in agreement with, for example, Yu & Ho (2019). Such a relation is predicted by the density wave theory. However, the very large scatter in this relation

observed in Yu & Ho (2019), as well as in this study, is not consistent with the density wave theory (Masters & Galaxy Zoo Team 2020). In Font et al. (2019), a dependence between disc mass fraction and pitch angle of spiral arms was examined for barred galaxies. They did not find any correlation between these parameters, albeit there are no galaxies with low-disc mass fraction (and therefore with a massive bulge) and a high-pitch angle at the same time. Kendall, Clarke & Kennicutt (2015) found no relation between pitch angle and concentration parameter, which can be considered as a proxy of B/T . Finally, Davis et al. (2015) reported that the pitch angle decreases with increasing bulge mass.

We also investigate a connection between $\langle \Delta\mu \rangle / \langle \mu \rangle$ and spiral-to-total luminosity ratio S/T . In Fig. 12, we see a fairly weak anticorrelation between these two quantities, but we note that $\langle \Delta\mu \rangle / \langle \mu \rangle$ is always small for galaxies with a high S/T . In other words, galaxies with a strong spiral structure have spiral arms close to logarithmic (Fig. 12). Savchenko et al. (2020) found the same dependence. Assuming that Hubble type T is connected with both $\langle \mu \rangle$ and S/T (see Figs 10 and 8, respectively), one can think that this relation arises purely from these two relations. However we notice an even stronger relation between $\langle \Delta\mu \rangle$ and S/T , which proves that stronger spiral arms indeed have shapes closer to logarithmic spirals.

6.3 Spiral arm width

We define the width of a spiral arm as the FWHM of a radial slice in the middle of the arm, i.e. at $\varphi = \varphi_{\text{end}}/2$. We note that w_e^{in} and w_e^{out} in equation (5) are connected with the width itself not in a simple way, and $w_e^{\text{in/out}}$ itself is a value of limited usefulness. The Sérsic profile implies a symmetric 2D distribution of light, and, in its definition, the effective radius r_{eff} is a radius enclosing half of the galaxy flux.

The denominator in equation (5) ($w_\varphi^{\text{in/out}} = \sqrt{(w_e^{\text{in/out}})^2 + (\varphi \times \xi)^2}$ for short) is similar to r_{eff} in its form, but the Sérsic-like distribution of light in our model is only one-dimensional. If we consider the band of inner/outer half-width of $w_\varphi^{\text{in/out}}$, it will not enclose precisely a half of luminosity of the spiral, and the specific fraction of light

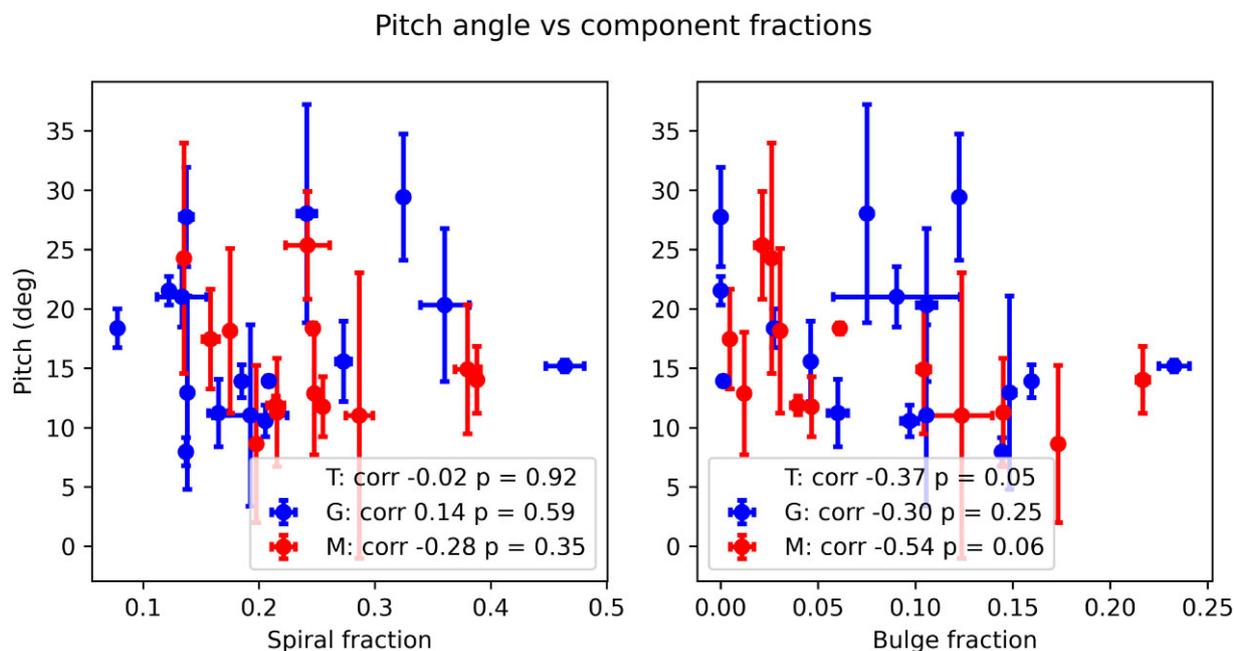


Figure 11. Diagrams showing pitch angle versus S/T (left) and B/T (right).

Pitch angle variation correlations

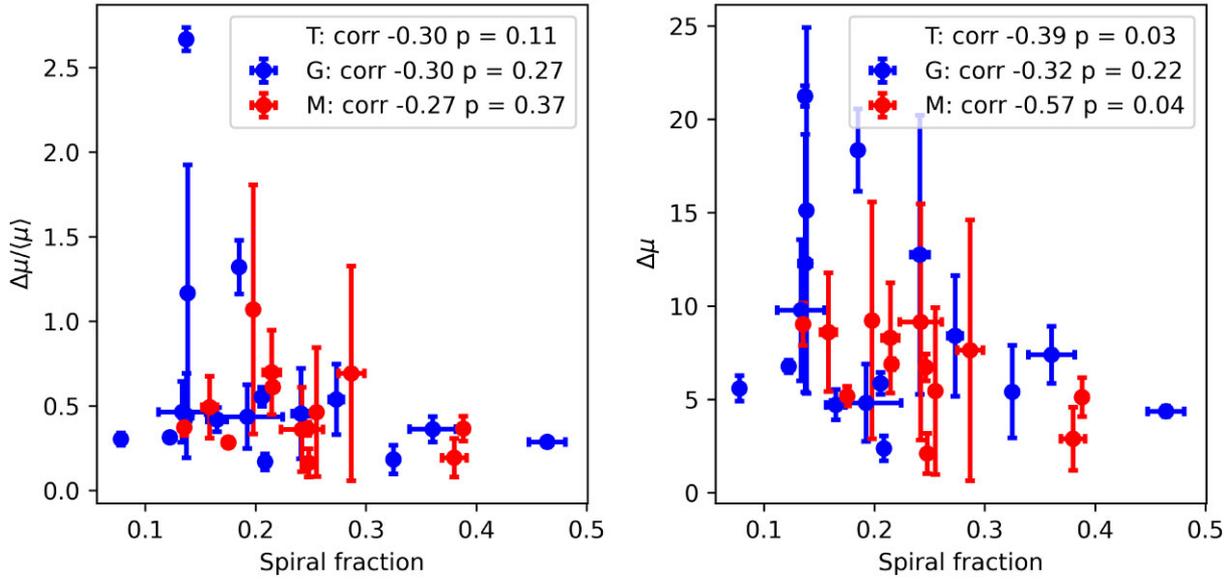


Figure 12. Diagrams showing correlations between pitch angle variation $\langle \Delta\mu \rangle$ or $\langle \Delta\mu \rangle / \langle \mu \rangle$ with spiral-to-total ratio S/T or Hubble type T .

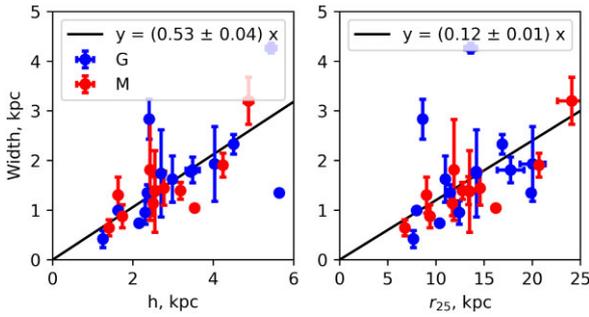


Figure 13. Relation between the width of spiral arms and disc scale length h (left) and radius r_{25} (right).

enclosed will depend on $n^{\text{in/out}}$. Therefore, we use the FWHM as a measure of width of the spiral arm, which is simply a sum of w_{in} and w_{out} . These values are measured from the ridge-line of the spiral arm to locations of half-maximum intensity along the radius.

Using the result of our fitting, we find a linear relation between the width of spiral arms w and disc scale length h and disc optical radius r_{25} . As seen in Fig. 13, $w = (0.53 \pm 0.04) h$ and $w = (0.12 \pm 0.01) r_{25}$, on average. For the r band, Savchenko et al. (2020) found $w = 0.16 r_{25}$, although the authors used a different method to measure the width which appears to be larger for the same distribution of light. Moreover, the width of galaxy spiral arms is not constant with wavelength and Marchuk et al. (in preparation) found for M 51 that the width of spiral arms is higher in the r band than at $3.6 \mu\text{m}$. The relationships between w and r_{25} or between w and h demonstrate that the size of spiral structure is proportional to the galaxy size, as expected. Perhaps, these relations are simply a typical example of scaling relations: when galaxies get physically bigger, many other structural parameters grow proportionally (an example is the correlation between the disc scale height and disc scale length, Mosenkov, Sotnikova & Reshetnikov 2010). Additionally, the Tully–Fisher relation (Tully & Fisher 1977) can be linked to those in Fig. 13. It relates the luminosity of the galaxy (which is, in turn, connected

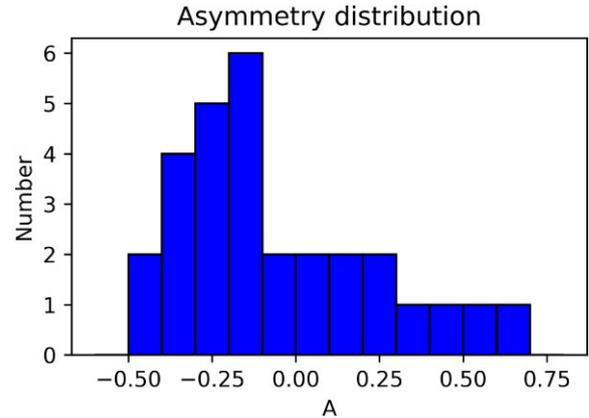


Figure 14. Distribution of the asymmetry of spiral arms' perpendicular profile. If outer part extends further from the spiral arm ridge, the value is positive.

with its mass and size) and its rotation velocity. If the disc rotates faster, the total range of differences between the velocity of spiral pattern and the disc matter in the various galaxies becomes higher. Therefore, young stars move away from the location of ongoing star formation faster and can be found further from it, making spiral arms wider (Marchuk et al. 2024).

The asymmetry of spiral arms can also be measured. We express the asymmetry in terms of the relative difference between the inner and outer widths $A = \frac{w_{\text{out}} - w_{\text{in}}}{w}$, so that A ranges from -1 to 1 in most extreme cases possible and equals 0 when the arm is symmetric. The distribution of A is shown in Fig. 14, and the mean value of A for galaxies in our sample is close to zero but negative, namely -0.05 . This means that there is a weak systematic asymmetry, with the inner part of spiral arms being more extended than the outer part, with respect to the spiral arm ridge. Interestingly, the distribution of A looks highly asymmetric and about $2/3$ of galaxies have negative A but the range of possible values of A is more extended to positive

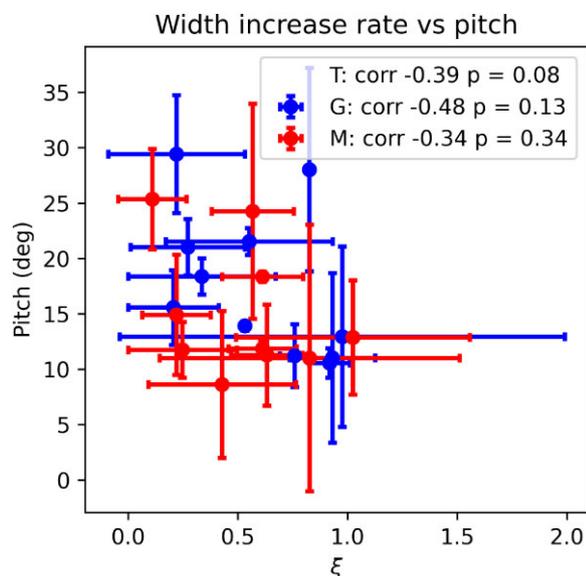


Figure 15. Diagram showing the pitch angle versus the spiral arm width increase rate ξ .

values than to negative (there are no galaxies with $A < -0.5$ but $A > 0.6$ is possible). Savchenko et al. (2020) found a positive average asymmetry indicating that the outer part of spiral arms is usually more extended than the inner one. They measure asymmetry as $A' = \frac{w_{\text{out}} - w_{\text{in}}}{w_{\text{out}}}$ which we consider less convenient and our values cannot be compared directly with theirs but, nevertheless, we obtain the qualitatively opposite conclusion which should not change if we adopt their definition of asymmetry. However, Savchenko et al. (2020) used r -band images for their analysis, so our and their results regarding asymmetry may differ significantly, because different photometric bands highlight different populations of stars in galaxies, which may be distributed differently inside the spiral arm.

We also examine the ξ value which determines the spiral arms width increase rate, defined in Section 3 (see equation 5). This value is restricted to non-negative values. In Fig. 15, we show pitch angles plotted versus ξ for $0 < \xi < 1.1$. A very subtle but clear trend can be seen that width increases more rapidly in more tightly wound arms. We should note that parameter ξ itself has a rather inconvenient dimension of $\text{arcsec}^{2/3} \text{rad}^{-1}$ (see equation 5), though this parameter allows one to obtain a good approximation of the spiral arm's shape. Most individual spiral arms have a non-zero positive ξ , indicating that their width is not constant and increases to periphery. On average, the arm width at the beginning is 74 per cent of the arm width at the end. Hydrodynamical simulations in Forgan, Ramón-Fox & Bonnell (2018) do not reproduce any noticeable width alteration with radius, whereas Savchenko et al. (2020) measurements show that width in most cases increases with radius, which is in agreement with our results. Honig & Reid (2015) measured the arm properties via the distribution of H II regions and also found that the arm width increases outwards. Interestingly, they found a reversal of this trend in the periphery of the arm, which cannot be reproduced with our model.

We also examine the scatter of individual spiral arms' width in each galaxy, measured as a ratio between the standard deviation of spiral arm width σ_w and their mean value $\langle w \rangle$, see Table 4. We find that $\sigma_w / \langle w \rangle$ is 23 per cent, on average, indicating that width variation in a single galaxy is usually not very high. We notice that the average $\sigma_w / \langle w \rangle$ is only 10 per cent for two-armed galaxies (with σ_w being

simply a half of width difference between two arms in this case), and 37 per cent for others. The lower $\sigma_w / \langle w \rangle$ for two-armed galaxies agrees with the fact that grand-design galaxies are known to have more symmetric spiral structure.

6.4 Connection with bar parameters

Various studies point to a connection between spiral arms and bars in galaxies (Athanasoula et al. 2010; Minchev et al. 2012). Most of the galaxies in our sample are barred, and different observed or predicted relations can be verified.

We find that pitch angle weakly decreases and the ratio between the spiral luminosity and disc luminosity (spiral-to-disc ratio, S/D) increases with increasing bar-to-total ratio (Bar/T), see Fig. 16. Interestingly, if S/T is plotted against Bar/T , the correlation will be slightly negative, in contrast, at first sight, to the positive Bar/T - S/D correlation. We can explain it by the fact that strongly barred galaxies obviously have a smaller fraction of the total flux contained in the other components except the bar and spirals, and S/D for strongly barred galaxies will be significantly higher than S/T . Moreover, three galaxies with strongest bars in our sample, namely NGC 986, NGC 4314, and NGC 4548, have a complex structure consisting of other components besides disc, bulge, and bar, making S/T for these galaxies even smaller compared to S/D .

Concerning the relation between pitch angle and bar-to-total ratio, Díaz-García et al. (2019) did not find any correlation between these quantities, whereas the results from Font et al. (2019) are consistent with ours. Both Bittner et al. (2017) and mentioned Díaz-García et al. (2019) found a positive correlation between spiral contrast and bar contrast, which agrees with our result. Note that, only grand-design galaxies in our sample host strong bars, whereas multi-armed galaxies have $\text{Bar}/T < 0.1$ and more often have no bar. This is consistent with Hart et al. (2017) and again points to a strong connection between the bars and spirals.

6.5 The light distribution in spirals along the radius

In this subsection, we analyse the contribution of the spiral arms to azimuthally averaged surface brightness profiles of the sample galaxies. For this purpose, we use a function $S/T_{\text{az}}(r)$, which represents the fraction of light provided by the spiral arm model at radius r . In Fig. 17, we give a few examples of $S/T_{\text{az}}(r)$ for galaxies in our sample.

We find that in almost all cases the function $S/T_{\text{az}}(r)$ reaches its maximum value at a moderate r , decreasing to zero in the centre and in the periphery of the galaxy. The only exception is NGC 2460, where $S/T_{\text{az}}(r)$ continues to increase far beyond the disc and reaches almost unity. We can conclude that in the vast majority of galaxies, spiral arms are truncated at smaller distances than the disc is. For NGC 2460, the opposite behaviour can be explained by the presence of IC 2209 in its neighbourhood, and their possible interaction might have formed the extended tidal arms in the NGC 2460. The drop of $S/T_{\text{az}}(r)$ to zero near the centre in all cases is easily explained by the fact that spiral arms are not observed in the very centre of galaxies and bulge contributes the most in the centre.

There are many galaxies with average h_s/h larger than unity (see Table 4), which means that spiral arms may have higher exponential scale than the disc and, thus, fade slower with radius in some part of disc. However, almost all of the galaxies have their arms truncated at some radius, which is apparently caused by the termination of star formation when gas density falls below the critical value (Kregel &

Bar fraction correlations

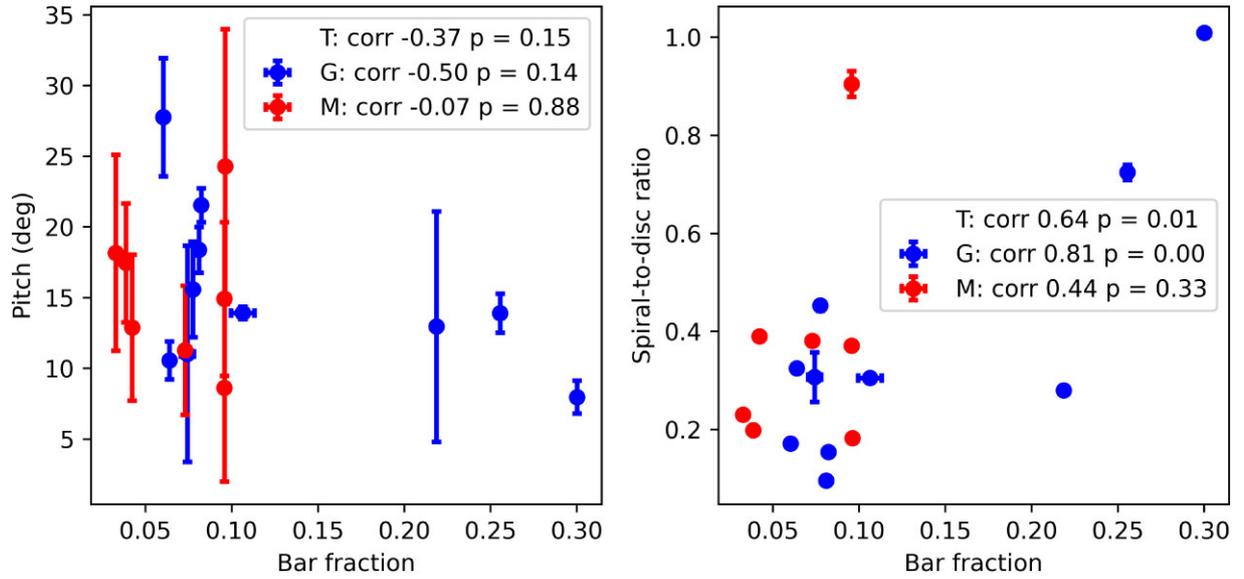


Figure 16. Correlations of bar fraction and spiral properties (only barred galaxies are included).

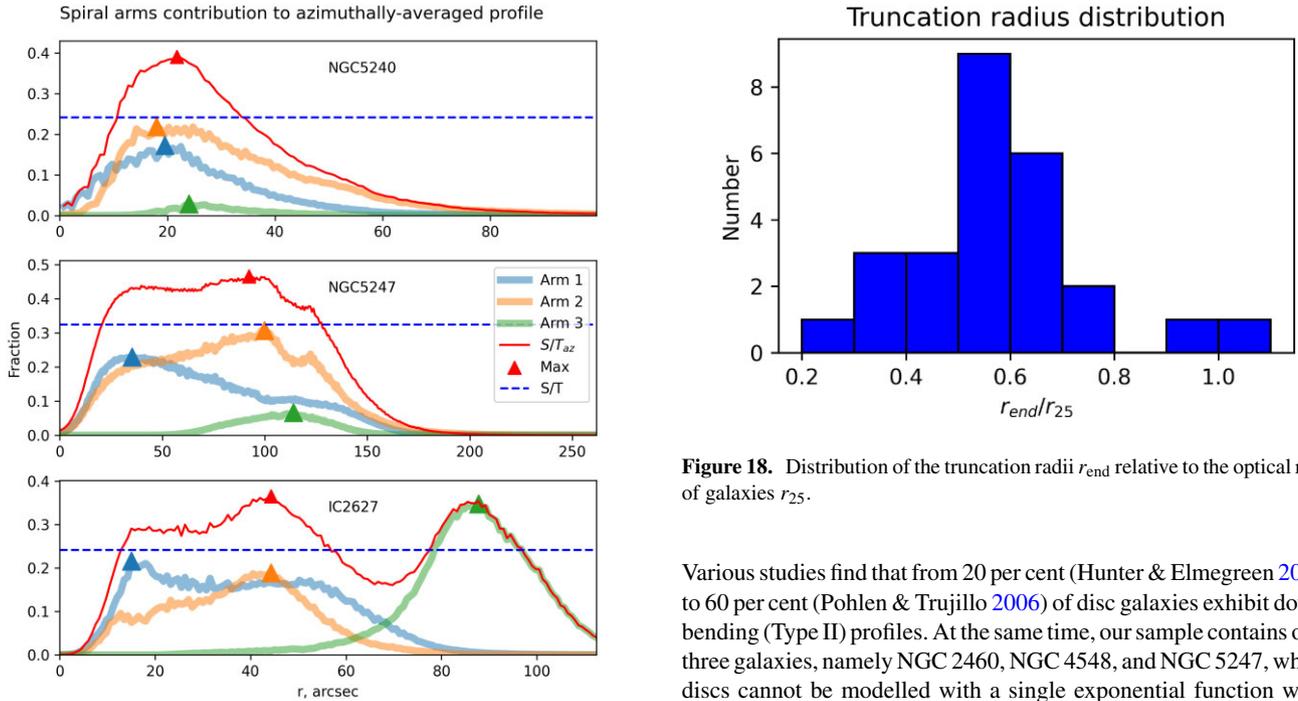


Figure 17. Examples of azimuthally averaged profile of spiral arms contribution, expressed as a $S/T_{az}(r)$ function. Each galaxy is an example of one of three main types of profiles. The function $S/T_{az}(r)$ for NGC 5240 has a single peak, for NGC 5247 it has a ‘plateau’, and for IC 2627 multiple peaks are seen. Similar images for other galaxies can be found in Appendix.

van der Kruit 2004). For our sample, the average truncation radius of spiral arms in a galaxy r_{end} usually lies between 0.5 and 0.7 of its optical radius r_{25} (Fig. 18) but the full range of possible values of r_{end}/r_{25} is large. Such a truncation is thought to be one of the reasons for the appearance of disc downbending profiles, i.e. transitions to smaller disc radial scale length at certain radius (Bittner et al. 2017).

Figure 18. Distribution of the truncation radii r_{end} relative to the optical radii of galaxies r_{25} .

Various studies find that from 20 per cent (Hunter & Elmegreen 2006) to 60 per cent (Pohlen & Trujillo 2006) of disc galaxies exhibit down-bending (Type II) profiles. At the same time, our sample contains only three galaxies, namely NGC 2460, NGC 4548, and NGC 5247, whose discs cannot be modelled with a single exponential function when spiral arms are included in the model, and, instead, are fitted with a broken exponential. Only the latter two have genuine down-bending profiles apparently not connected with spiral arms, which is less than 10 per cent of our sample. Since we expect a larger fraction of such profiles (Hunter & Elmegreen 2006; Pohlen & Trujillo 2006), we cautiously conclude that the truncation of spiral arms may be connected with down-bending of disc profiles (see Mosenkov et al. in preparation).

We also show that the behaviour of $S/T_{az}(r)$ near its maximum also varies between galaxies, see Fig. 17 again. We distinguish three main shapes of this function. The first type is one well-localized maximum, as in NGC 5240. The second type is a ‘plateau’, i.e. an extended zone where $S/T_{az}(r)$ is nearly constant, as in NGC 5247. The

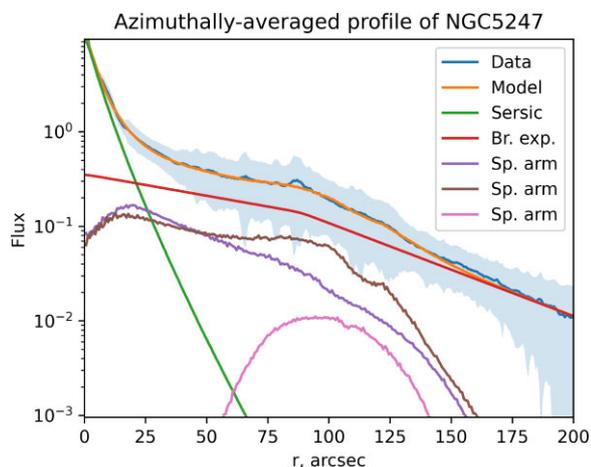


Figure 19. Azimuthally averaged profile of NGC 5247. At $r = 100 \dots 150$ arcsec, one can see that the spiral arms are truncated and the surface brightness of the whole galaxy becomes disc-dominated. At smaller r , the spirals make the overall profile brighter than the pure exponential, which is manifested as a ‘bump’ on the profile.

last type is characterized by multiple local maxima, usually produced by separate spiral arms, as in IC 2627.

The analysis of the Fourier modes’ amplitude relative to axisymmetric components in Kendall, Kennicutt & Clarke (2011) closely resembles our analysis of azimuthally averaged profiles. The amplitude of the Fourier modes in their analysis varies with radius and usually decreases near the centre, in agreement with our results. However, they traced amplitudes only out to the optical radius or even to a fraction of it, so we cannot compare our and their results regarding the decrease of $S/T_{az}(r)$ in the periphery. We have only one common galaxy with their study, namely NGC 5194 (M 51), and they traced it up to about 275 arcsec from the centre (see fig. 45 in Kendall, Kennicutt & Clarke 2011). In this range, our results are roughly consistent with theirs.

We will now discuss azimuthally averaged profiles of galaxies as a whole. In Fig. 19, one can see a profile of NGC 5247, shown as an example. In the periphery of the galaxy, where the truncation of the spiral arms occurs, only the disc component contributes to the surface brightness because the profile is purely exponential. Let us now consider the radius r_{peak} where $S/T_{az}(r)$ reaches its maximum. We can say that only the spiral arms and the disc are contributing to the profile at r_{peak} because the contribution of the central components, such as the bulge, is insignificant in the region where the spiral arms are most prominent. We can define $T/D_{az}(r)$ as a function representing the ratio of the azimuthally averaged surface brightness of the galaxy and the same but for the disc model only. It is known that spiral arms create a ‘bump’ over a pure exponential surface brightness profile of the disc, for example, see Casasola et al. (2017). The prominence of this bump can be expressed as $T/D_{az}(r_{\text{peak}})$, since we have shown that only disc and spiral arms are contributing to the profile at r_{peak} , and the contribution of the spiral arms is the highest there. It is thus natural to assume that the prominence of the bump is related to the spiral-to-total luminosity ratio.

In Fig. 20, we show the relation between $T/D_{az}(r_{\text{peak}})$, expressed in magnitudes, and S/T . We see three outliers from this relation, of which the aforementioned NGC 2460 stands out the most. It can be excluded from the relation because its spiral arms extend farther than the disc and so their contribution in the periphery is much higher than the disc’s contribution. The other two outliers are

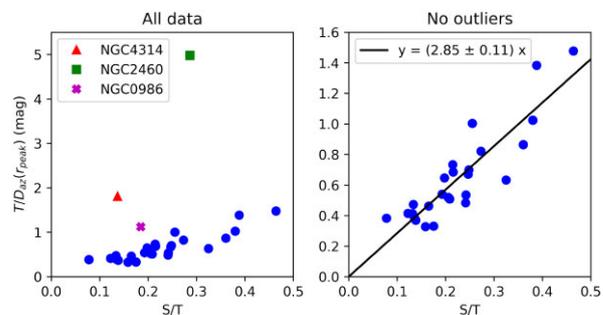


Figure 20. Relation between the $T/D_{az}(r_{\text{peak}})$ and S/T . Values for all galaxies in the sample are shown on the left, outliers are marked with non-circular symbols. The same relation with outliers excluded and linear approximation shown is on the right.

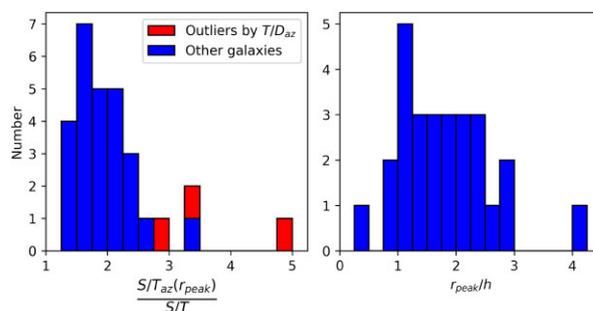


Figure 21. On the left, the distribution of the ratio of $T/D_{az}(r_{\text{peak}})$ to S/T is shown, with the outliers from Fig. 20 marked with red. On the right, the distribution of the ratio of the r_{peak} to disc exponential scale is shown.

NGC 986 and NGC 4314 which have luminous central components, bars, and rings and, therefore, their disc-to-total luminosity ratios are low. At the same time, spiral arms in these galaxies form outer pseudorings, and these contribute mostly at large radii, where the discs are faint. If we exclude these outliers, we will obtain the relation $T/D_{az}(r_{\text{peak}})(\text{mag}) = (2.85 \pm 0.11) S/T$. Assuming that S/T is usually between 0.1 and 0.25, the typical bump on the azimuthally averaged profile atop the pure exponential is 0.3–0.7 mag, but we see that for galaxies with the most prominent spiral structure it exceeds 1.4 mag. Using this relation, one can estimate the spiral-to-total luminosity ratio solely from an analysis of azimuthally averaged profile.

In Fig. 21, the left-hand side, we show a distribution of $S/T_{az}(r_{\text{peak}})/(S/T)$, i.e. the ratio between the highest contribution of the spiral arms to the azimuthally averaged profile and the overall spiral-to-total ratio, which lies in most cases between 1.5 and 2.5. In Fig. 21, the right-hand side, we show a distribution for r_{peak}/h . We find that the contribution of the spiral arms to the azimuthally averaged profile is usually the highest at a distance of 1–2 disc radial scale lengths from the center.

6.6 Difference between pure stellar and original images

We study the decomposition results for the original 3.6 μm images and pure stellar images for a sample of 5 galaxies: IC 2627, NGC 895, NGC 3686, NGC 4680, and NGC 5247. Needless to say, the characteristic surface brightness of all components decreases in most cases, because the exclusion of hot dust and PAH emission makes the overall luminosity of the galaxy smaller. For our subsample, stars make up, on average, 79 per cent of the total galaxy light in the 3.6 μm

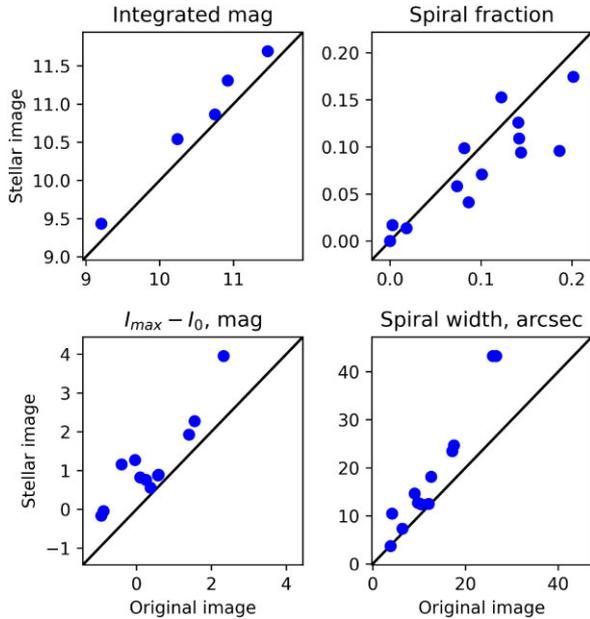


Figure 22. Difference of measured parameters between models for original image and pure stellar image. Upper left: integrated AB magnitude in $3.6\ \mu\text{m}$ band; upper right: spiral-to-total ratio; lower left: contrast of spiral arms (difference between I_{max} of the spiral arm and I_0 of the disc); lower right: spiral arm width. The latter three plots show comparisons for individual spiral arms.

band, which is consistent with values of 70–80 per cent, depending on Hubble type, found in Querejeta et al. (2015). Apart from the decrease of the overall luminosity, we find significant systematic differences in the estimated parameters of the spiral arms, while the parameters of other components remain essentially the same. In Fig. 22, we show the changes of some parameters. In general, on pure stellar images the spiral arms clearly become less contrast but wider, and their contribution to the overall luminosity slightly decreases. We can describe the contrast of spiral arms as the difference between I_{max} of the spiral arm and I_0 of the disc, expressed in magnitudes. On average, the contrast becomes 0.78 mag lower, while the width increases by 50 per cent. The overall fraction of spiral arms in the total stellar luminosity decreases by 21 per cent.

Such behaviour is not surprising, since PAH and hot dust emission are connected not only to the mass distribution but also to ongoing star formation. One can naturally expect that their radiation will be concentrated to spiral arms much stronger than the stellar emission, which makes spirals in pure stellar images overall less contrast and fainter than in the original images. Indeed, there are various studies (e.g. Savchenko et al. 2020) which show that spiral arms in the optical domain make a smaller contribution to the total galaxy emission towards redder bands that highlight the older stellar population. On the other hand, the radiation associated with PAH and hot dust cannot spread as far from the region of ongoing star formation as radiation produced by an older stellar population, which makes spirals in pure stellar images wider. This is consistent with Pessa et al. (2023) who show that older stellar populations demonstrate wider spiral arms. These results are also in agreement with our multiwavelength study of M 51 (Marchuk et al., in preparation) where it is shown that the spiral arms width is the highest and their contribution is the lowest in red and near-infrared bands, mostly associated with the old stellar population.

7 DISCUSSION

We have found that the parameters of galactic structural components, derived by means of photometric decomposition, are prone to systematic errors when spiral arms are not accounted for. This was shown in Sonnenfeld (2022) by the analysis of some model galaxies, while here, we demonstrate the same result for a sample of real galaxies. The inclusion of spiral arms in the model is especially important for the disc brightness. We have also found that the presence of spiral arms produces a ‘bump’ on the galaxy azimuthally averaged surface brightness profile. This means that if one measures the parameters of a spiral galaxy without treating the spiral arms properly, the estimates may be erroneous, even if one uses other methods than decomposition, e.g. azimuthally averaged profile analysis. This may have far-reaching consequences. In particular, various known scaling relations for spiral galaxies or their components (D’Onofrio, Marziani & Chiosi 2021) may need to be reconsidered to take this effect into account. Most obviously, the known distribution of the central disc surface brightness I_0 (O’Neil & Bothun 2000) probably should be adjusted, because its value is commonly determined by extrapolation of the disc brightness profile to the centre. Assuming that the height of the mentioned ‘bump’ is usually 0.3–0.7 mag at $3.6\ \mu\text{m}$, the required correction to the measured μ_0 should be of the same order of magnitude.

Apart from introducing biases in the scaling relations, neglecting spiral arms in the decomposition leads to significant errors at the level of individual galaxies. Therefore, a proper treatment of spiral arms may reduce the uncertainty of these parameters and minimize the scatter in physically significant scaling relations. For example, a photometric distinction between classical bulges ($n > 2$) and pseudobulges ($n < 2$) is well known (see e.g. Gadotti 2009), and different scaling relations demonstrate the difference of these two types of bulges (Gadotti 2009; Fisher & Drory 2010). Since estimation of the Sérsic index n in decomposition can be affected by the presence and brightness of spiral arms in a galaxy, it is possible that some of those bulge scaling relations can be influenced to some degree as well.

Photometric decomposition is the most straightforward way to distinguish the light from spiral arms and main galaxy components, if a suitable model of spirals is used. At the same time, decomposition with spiral arms allows one to measure a large set of parameters of spiral arms. The main problem is that such method is time-consuming and not easy to implement, which limits the possible sample size. Nevertheless, our results show various connections between some parameters of spiral arms and other components, implying that it is possible to establish some scaling relations for spiral arms and define a small number of key parameters of spiral structure related to other structural parameters and general properties of galaxies. In this paper, we have determined some of these key parameters. For instance, the spiral-to-total luminosity ratio seems to be important for understanding the origin of different types of spiral structure.

Previously, decomposition was not used widely for the determination of spiral arms parameters. Therefore, it is important to examine the general consistency of our results with other methods used in the literature. The good starting point is the study by Díaz-García et al. (2019), since our subsample of galaxies was selected from their much larger sample, and we utilize the same S⁴G data. They measured pitch angles of spiral arms using a Fourier technique. A quick comparison with our results shows that our average pitch angles are roughly consistent with theirs for individual galaxies. Moreover, the agreement between our results and Díaz-García et al. (2019) is not worse than the agreement between their results and other studies

employing the same Fourier technique (see for example fig. 5 in their paper). We also compare our results with Savchenko et al. (2020) since they measured various parameters of spiral arms using a very direct method of making and analysing perpendicular slices of spiral arms. Although they used a different set of galaxies and different wavelengths (*gri*), our conclusions concerning the width of spiral arms and their contribution to the total luminosity are remarkably consistent with theirs. This proves that our complex modelling of galaxy structure with spiral arms is a credible approach to determine the parameters of spiral structure.

Decomposition, if done for a multiband set of galaxy images, can also be important for separately studying resolved spectral energy distributions (SEDs) of different galaxy subsystems, such as a disc and a bulge. This makes it possible to reconstruct the star formation rate and assembly history of these components. This approach has been successfully applied to the lenticular galaxy NGC 3115 by Buzzo et al. (2021) and more recently for M 81 in Gong et al. (2023). In the latter case, it is easy to see in the residuals map (Figs 17 and 19) that the enormous spiral arms of M 81 were not included in their model. The spiral arms should usually have a similar stellar history as the underlying stellar disc. However, our results for 3.6 μm in this paper and for a multiwavelength data set for M 51 in Marchuk et al. (in preparation) also demonstrate that the SED of the bulge may be affected, if spiral arms are not properly accounted for in modelling. Therefore, in future studies, these considerations should be taken in account when spiral arms have a significant contribution to the galaxy SED.

Our analysis has shown that spiral arm model, which is adopted in our work, is suitable for fitting spiral arms. However, it has some drawbacks which were revealed when applying it in practice. Some of these issues are mostly technical and their correction will not alter the form of the functions that defines our model. At first, this concerns the exact set of values which are used as input parameters of functions in IMFIT input files. For example, instead of the pair of φ_{cutoff} and φ_{end} , we can redefine the function to use the equivalent pair of φ_{cutoff} and $\varphi_{\text{end}-\varphi_{\text{cutoff}}}$, where the latter has physical meaning of length of the cutoff region. However, the first pair of values is more convenient to use because the position of φ_{cutoff} and the length of the cutoff region has some degeneracy when both used as free parameters.

Even though our model has a large number of free parameters and is flexible enough to properly account for intricate details of spiral arms, such as a variable pitch angle and widening, the application of our model to real galaxies revealed that there is still room for improvement of the model. For example, in our model, the half-width can only increase on the inner and outer sides of the arm with the same rate. However, it would be more accurate to consider independent rates of the width's change on both sides of the arm. This can be justified by the following physical reasons. Because the spiral arms in a galaxy rotate faster than the disc outside the corotation radius and slower inside of it, the matter enters a spiral arm from different sides in the central and peripheral parts of the galaxy. When material enters the arm, star formation occurs. The formed young stellar population then leaves the arm on the opposite side of the arm (see e.g. Martínez-García, González-Lópezzira & Puerari 2023), and the 'trail' of young stars makes one side more extended than another. For a trailing spiral arm, in the central part of galaxy, the outward side will be more extended, and in the periphery the opposite will be true (Marchuk et al. 2024). Therefore, a half-width of the spiral arm can indeed change for the inward and outward sides of the arm independently. In future, we plan to improve our model and use a greater number of bands. It will allow us to locate corotation radii

in galaxies (Marchuk et al. 2024), which is of great importance for studying the dynamics of galaxies. The forthcoming papers in series will be devoted to the multiwavelength study of M 51 (Marchuk et al. in preparation) and to the study of distant galaxies up to $z \approx 1$ (in preparation).

8 CONCLUSIONS

Galaxies with a prominent spiral pattern are ubiquitous in the local Universe, but spiral arms are rarely taken into account in the photometric decomposition of galaxies. In this paper, we have attempted to remedy this lack and draw the following conclusions:

(i) We have applied a new photometric model of spiral arms, which describes the 2D distribution of surface brightness independently for each spiral arm. Our function has an advantage that all its parameters have a clear physical meaning. It can accurately reproduce real spiral arms with a different geometry, including those with variable widths and pitch angles, and with a different distribution of light both along and across the arm. Using this function, we have performed decomposition of 29 spiral galaxies which is enough to conduct a statistical analysis of our results.

(ii) We have compared 'classical' models consisting only of commonly used components (disc, bulge, bar, etc.) and models with spiral arms for each galaxy. We measured how neglecting the spiral arms affects the estimation of parameters in our sample. After including the spiral arms in the model, surface brightness of the disc decreases by 0.5 mag at average. We found that parameters of the bulges and bars, as well as the disc exponential scale, are also change significantly when including spiral arms; however, in most cases these changes are different for different galaxies.

(iii) We have confirmed that spiral arms can contribute significantly to galaxy luminosity. Their contribution is usually 10–25 per cent but, in some galaxies, it may exceed 45 per cent of the total luminosity in the 3.6 μm band. We found that spiral arms contribution is higher for galaxies with a higher bulge-to-total ratio and which host more luminous discs, as well as for galaxies of intermediate Hubble types (see Figs 8 and 9). Some of these results have been reported by Savchenko et al. (2020), but in this paper we have obtained them using the accurate photometric decomposition for the first time.

(iv) Our method has allowed us to measure pitch angles for each spiral arm independently and also trace the variability of the pitch angle along the spiral arm. We found that the pitch angle variation in a single spiral arm is 8°, on average. Therefore, we conclude that spiral structure in galaxies cannot be generally characterized by a single pitch angle, or even by average pitch angles of individual arms. We confirm the weak anticorrelation between pitch angle and bulge fraction, which was found in some previous studies, but using our new method. We confirm that the pitch angle variation is the smallest in galaxies with the most prominent spirals, again in consistency with Savchenko et al. (2020).

(v) We have measured the widths of the spiral arms and find that the width, expressed in terms of FWHM, in on average equal to 53 per cent of the disc scale length or 12 per cent of the disc optical radius (see Fig. 13). We found a weak systematic asymmetry of the perpendicular profiles of spiral arms, with inner parts being little more extended than outer. We measured the rate of width increase along the spiral arms and found that the width at the beginning of arms is 73 per cent of the width at the end of arms, on average.

(vi) We have inspected the connection between the parameters of the bar and the spiral arms, and found that pitch angle weakly decreases and spiral-to-disc ratio increases with an increase of the bar

fraction (see Fig. 16). We also confirm that strongly barred galaxies tend to have grand-design spiral structure.

(vii) We have analysed the contribution of the spiral arms to the azimuthally averaged galaxy profiles. In almost all cases, the contribution of spiral structure reaches its highest value at moderate radii, usually at 1–2 disc scale lengths from the centre, decreasing to zero near the centre and in the periphery of the galaxy. We found a relationship between the spiral-to-total luminosity ratio and the size of the ‘bump’ on the azimuthally averaged profile associated with the presence of the spirals. We found its typical value to be 0.3–0.7 mag.

(viii) We have compared the decomposition results for the original 3.6 μm -band images and pure stellar images from Querejeta et al. (2015) for a subset of 5 galaxies. We have found that, on average, on pure stellar images the spiral arms become 0.78 mag less contrast, 50 per cent wider, and their contribution to the overall luminosity decreases by 21 per cent.

Overall, we conclude that various estimates of the galaxy parameters in the literature, which do not account properly for the presence of spiral arms, are likely to be biased. This may have far-reaching consequences for some scaling relations of spiral galaxies and, thus, such relations need to be updated using accurate photometric decomposition with spiral arms included.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

REFERENCES

- Athanassoula E., Romero-Gómez M., Bosma A., Masdemont J. J., 2010, *MNRAS*, 407, 1433
- Bailer-Jones C. A. L., 2017, *Practical Bayesian Inference: A Primer for Physical Scientists*. Cambridge University Press, Cambridge
- Binney J., Tremaine S., 2008, *Galactic Dynamics: Second Edition*. Princeton University Press, Princeton, NJ
- Bittner A., Gadotti D. A., Elmegreen B. G., Athanassoula E., Elmegreen D. M., Bosma A., Muñoz-Mateos J.-C., 2017, *MNRAS*, 471, 1070
- Bizyaev D. V., Kautsch S. J., Mosenkov A. V., Reshetnikov V. P., Sotnikova N. Y., Yablokova N. V., Hillyer R. W., 2014, *ApJ*, 787, 24
- Block D. L., Bertin G., Stockton A., Grosbol P., Moorwood A. F. M., Peletier R. F., 1994, *A&A*, 288, 365
- Buta R. J. et al., 2015, *ApJS*, 217, 32
- Buzzo M. L. et al., 2021, *MNRAS*, 504, 2146
- Cappellari M. et al., 2013, *MNRAS*, 432, 1862
- Casasola V. et al., 2017, *A&A*, 605, A18
- Conselice C. J., 1997, *PASP*, 109, 1251
- Conselice C. J., 2006, *MNRAS*, 373, 1389
- D’Onofrio M., Marziani P., Chiosi C., 2021, *Frontiers Astron. Space Sci.*, 8, 157
- D’Souza R., Kauffman G., Wang J., Vegetti S., 2014, *MNRAS*, 443, 1433
- Davis B. L., Berrier J. C., Shields D. W., Kennefick J., Kennefick D., Seigar M. S., Lacy C. H. S., Puerari I., 2012, *ApJS*, 199, 33
- Davis B. L. et al., 2015, *ApJ*, 802, L13
- Díaz-García S., Salo H., Knapen J. H., Herrera-Endoqui M., 2019, *A&A*, 631, A94
- Elmegreen D. M., 1981, *ApJS*, 47, 229
- Elmegreen B. G., 1990, *Ann. New York Acad. Sci.*, 596, 40
- Elmegreen D. M., Elmegreen B. G., 1982, *MNRAS*, 201, 1021
- Elmegreen D. M., Elmegreen B. G., 1984, *ApJS*, 54, 127
- Elmegreen D. M., Elmegreen B. G., 1987, *ApJ*, 314, 3
- Erwin P., 2015, *ApJ*, 799, 226
- Erwin P. et al., 2021, *MNRAS*, 502, 2446
- Fisher D. B., Drory N., 2010, *ApJ*, 716, 942
- Font J., Beckman J. E., James P. A., Patsis P. A., 2019, *MNRAS*, 482, 5362
- Forgan D. H., Ramón-Fox F. G., Bonnell I. A., 2018, *MNRAS*, 476, 2384
- Freeman K. C., 1970, *ApJ*, 160, 811
- Gadotti D. A., 2008, *MNRAS*, 384, 420
- Gadotti D. A., 2009, *MNRAS*, 393, 1531
- Gadotti D. A. et al., 2020, *A&A*, 643, A14
- Gao H., Ho L. C., 2017, *ApJ*, 845, 114
- Gong J.-Y., Mao Y.-W., Gao H., Yu S.-Y., 2023, *ApJS*, 267, 26
- Hamilton C., 2023, preprint (arXiv:2302.06602)
- Hart R. E., Bamford S. P., Casteels K. R. V., Kruk S. J., Lintott C. J., Masters K. L., 2017, *MNRAS*, 468, 1850
- Honig Z. N., Reid M. J., 2015, *ApJ*, 800, 53
- Hunter D. A., Elmegreen B. G., 2006, *ApJS*, 162, 49
- Joye W. A., Mandel E., 2003, in Payne H. E., Jedrzejewski R. I., Hook R. N., eds, *ASP Conf. Ser. Vol. 295, Astronomical Data Analysis Software and Systems XII*. Astron. Soc. Pac., San Francisco, p. 489
- Kendall S., Kennicutt R. C., Clarke C., 2011, *MNRAS*, 414, 538
- Kendall S., Clarke C., Kennicutt R. C., 2015, *MNRAS*, 446, 4155
- Kennicutt R. C. J., 1981, *AJ*, 86, 1847
- Kregel M., van der Kruit P. C., 2004, *MNRAS*, 355, 143
- Laine J. et al., 2014, *MNRAS*, 441, 1992
- Lang D., Hogg D. W., Mykytyn D., 2016, *The Tractor: Probabilistic astronomical source detection and measurement*, Astrophysics Source Code Library, record: ascl:1604.008 (ascl:1604.008)
- Läsker R., Ferrarese L., van de Ven G., 2014, *ApJ*, 780, 69
- Lingard T. K. et al., 2020, *ApJ*, 900, 178
- Lingard T. et al., 2021, *MNRAS*, 504, 3364
- Makarov D., Prugniel P., Terekhova N., Courtois H., Vauglin I., 2014, *A&A*, 570, A13
- Marchuk A. A. et al., 2022, *MNRAS*, 512, 1371
- Marchuk A. A., Mosenkov A. V., Chugunov I. V., Kostiuk V. S., Skryabina M. N., Reshetnikov V. P., 2024, *MNRAS*, 527, L66
- Martínez-García E. E., González-Lópezlira R. A., Puerari I., 2023, *MNRAS*, 524, 18
- Masters K. L., *Galaxy Zoo Team*, 2020, *Proc. Int. Astron. Union*, 353, 205
- Meidt S. E. et al., 2012, *ApJ*, 744, 17
- Méndez-Abreu J. et al., 2017, *A&A*, 598, A32
- Minchev I., Famaey B., Quillen A. C., Di Matteo P., Combes F., Vlajić M., Erwin P., Bland-Hawthorn J., 2012, *A&A*, 548, A126
- Moré J. J., 1978, in Watson G. A., ed., *Numerical Analysis*. Springer Berlin Heidelberg, Berlin, Heidelberg, p. 105
- Mosenkov A. V., Sotnikova N. Y., Reshetnikov V. P., 2010, *MNRAS*, 401, 559
- Mosenkov A. V., Sotnikova N. Y., Reshetnikov V. P., Bizyaev D. V., Kautsch S. J., 2015, *MNRAS*, 451, 2376
- Mosenkov A. V., Savchenko S. S., Smirnov A. A., Camps P., 2021, *MNRAS*, 507, 5246
- O’Neil K., Bothun G., 2000, *ApJ*, 529, 811
- Papaderos P., Breda I., Humphrey A., Michel Gomes J., Ziegler B. L., Pappalardo C., 2022, *A&A*, 658, A74
- Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2002, *AJ*, 124, 266

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- Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2010, *AJ*, 139, 2097
 Pérez-Villegas A., Pichardo B., Moreno E., 2015, *ApJ*, 809, 170
 Pessa I. et al., 2023, *A&A*, 673, A147
 Pohlen M., Trujillo I., 2006, *A&A*, 454, 759
 Querejeta M. et al., 2015, *ApJS*, 219, 5
 Roberts M. S., Haynes M. P., 1994, *ARA&A*, 32, 115
 Salo H. et al., 2015, *ApJS*, 219, 4
 Savchenko S. S., Reshetnikov V. P., 2013, *MNRAS*, 436, 1074
 Savchenko S., Marchuk A., Mosenkov A., Grishunin K., 2020, *MNRAS*, 493, 390
 Sersic J. L., 1968, Atlas de Galaxias Australes. Observatorio Astronomico, Cordoba, Argentina
 Sheth K. et al., 2010, *PASP*, 122, 1397
 Simard L., Mendel J. T., Patton D. R., Ellison S. L., McConnell A. W., 2011, *ApJS*, 196, 11
 Smirnov A. A., Savchenko S. S., 2020, *MNRAS*, 499, 462
 Sonnenfeld A., 2022, *A&A*, 659, A141
 Tully R. B., Fisher J. R., 1977, *A&A*, 54, 661
 Vika M., Driver S. P., Cameron E., Kelvin L., Robotham A., 2012, *MNRAS*, 419, 2264
 Yu S.-Y., Ho L. C., 2019, *ApJ*, 871, 194
 de Vaucouleurs G., 1948, *Ann. d' Astrophys.*, 11, 247

SUPPORTING INFORMATION

Supplementary data are available at *MNRAS* online.

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APPENDIX A

In Fig. 23, we present the summarized decomposition results for ESO 508–024 galaxy, showing 2D images of galaxy and models, major-axis surface brightness profiles, spiral arms contribution to azimuthally averaged profile, as well as tables with the list of parameters of components. Similar figures for all 29 galaxies are available in the online material.

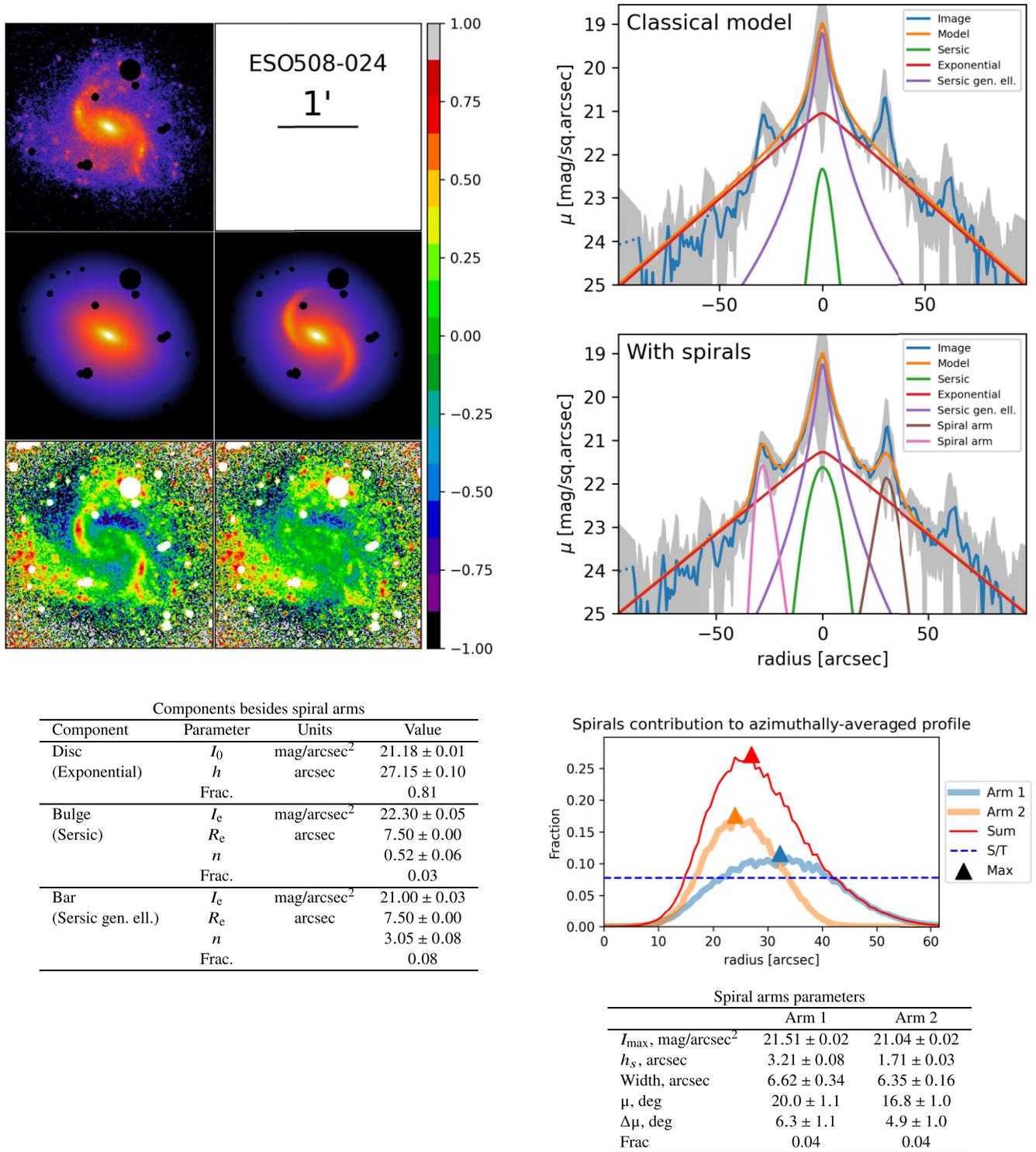


Figure 23. Decomposition results for ESO508–024. **Images:** Original image, models, and residuals (similar to Fig. 2) are at the top left. Surface brightness profiles of image, model, and individual components along the major axis are at the top right. A plot of the spiral arms contribution to the azimuthally averaged profile of galaxy (similar to Fig. 17) is at the lower right. **Tables:** List of ‘classical’ components and their parameters in the model with spiral arms is on the left. A list of the spiral arms with their parameters is on the right.

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