Morphological Deconstruction of the Early-type Spiral Galaxy M81 (NGC 3031)

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Abstract

Using the galaxy decomposition software GALFIT, we performed morphological decomposition of the nearby early-type spiral galaxy M81 (NGC 3031) through surface brightness profile fitting, aiming to investigate the structural composition of M81 and conduct morphological quantification. Through six decomposition modes, we performed structural decomposition of M81 with varying degrees of complexity, with the most complex decomposition mode containing five substructures: bulge, disk, outer spiral arms, inner spiral arms, and galactic nucleus. The research results show that M81 has a classical bulge with a S´ersic index of approximately 5.0, whose morphology and luminosity remain stable across different decomposition modes; the S´ersic index of the M81 galactic disk is approximately 1.2, but its morphological parameters and luminosity are correlated with whether the inner spiral arms are decomposed. The combination of different substructures has a non-negligible influence on the morphology of the galaxy as a whole, which acts as a composite system. The results of galaxy decomposition provide recommendations on the applicability of different decomposition modes: the three-component decomposition of bulge+disk+nucleus is suitable for bulge-disk studies of large galaxy samples; while complex decomposition considering spiral arms is suitable for precise measurements of galaxy substructures, such as in small-sample (or individual source) studies. The morphological decomposition study based on single-band images from Spitzer-The Infrared Array Camera (IRAC) 4.5 µm marks the beginning of a series of follow-up studies, upon which future work will perform multi-band decomposition of M81, simultaneously investigate the spectral energy distributions and stellar population properties of different substructures, and infer the formation history and evolutionary processes of each substructure in M81.

Full Text

Morphological Decomposition of the Early-type Spiral Galaxy M81 (NGC 3031)

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Abstract

We perform morphological decomposition of the nearby early-type spiral galaxy M81 (NGC 3031) by fitting surface brightness profiles using the galaxy decomposition software GALFIT, aiming to investigate the structural composition of M81 and quantify its morphology. Through six decomposition modes with varying complexity, we decompose M81 into different structural components, with the most complex mode containing five substructures: a bulge, a disk, outer spiral arms, inner spiral arms, and a galactic nucleus. The results demonstrate that M81 possesses a classical bulge with a Sérsic index of approximately 5.0, whose morphology and luminosity remain stable across different decomposition modes. The disk of M81 has a Sérsic index of approximately 1.2, but its morphological parameters and luminosity are sensitive to whether the inner spiral arms are decomposed separately. The combination of different substructures exerts a non-negligible influence on the overall morphology of the galaxy as an integrated system. The decomposition results provide recommendations regarding the applicability of different modes: the three-component decomposition (bulge+disk+nucleus) is suitable for large-sample studies of bulge-disk systems, while more complex decompositions that incorporate spiral arms are appropriate for precise measurements of individual galaxies in small samples (or single sources).

This single-band morphological decomposition study based on Spitzer-The Infrared Array Camera (IRAC) 4.5 μm images marks the beginning of a series of investigations. Building upon this work, we will conduct multi-wavelength decomposition of M81, simultaneously studying the spectral energy distributions and stellar population properties of different substructures, and inferring the formation history and evolutionary processes of each component in M81.

Keywords: galaxies: individual: M81, bulges, galaxies: fundamental parameters: morphology, galaxies: structure, galaxies: spiral

Galaxy morphology represents the most direct observational characterization of galaxies, with galaxy formation and evolution being the primary factors determining morphology. For instance, elliptical galaxies (or spheroidal galaxies) are generally believed to form through short-timescale violent processes such as mergers, which accelerate the collapse of internal gas, trigger starbursts that produce numerous stars, and disrupt the originally ordered stellar orbits to create spheroidal structures. These systems exhibit relatively smooth overall morphologies without distinct breaks or other substructures, with stellar motions dominated by random velocities and large velocity dispersions. In contrast, disk-dominated galaxies are thought to form through long-timescale accretion processes, creating orbitally ordered stellar systems that may develop spiral arms or other substructures under the influence of companion galaxies or asymmetric gravitational potentials, with stellar motions dominated by coherent rotation and small velocity dispersions. These different formation processes produce stellar populations with distinct properties: elliptical galaxies primarily host old stellar populations with low star formation activity and redder overall colors, while disk galaxies typically contain younger stellar populations with bluer colors and relatively higher star formation rates. Investigating galaxy morphology is fundamental to understanding the properties of stellar populations and the formation and evolution of galaxies.

A galaxy often comprises multiple substructures with different morphologies, particularly for disk galaxies whose main components are the bulge, disk, and spiral arms. The bulges of disk galaxies share similar observational characteristics with elliptical galaxies, including comparable surface brightness profiles, suggesting that bulges may form through short-timescale violent processes (like mergers) similar to elliptical galaxies. Early-type spiral galaxies formed their bulges at early evolutionary stages, while disk structures may have emerged later through gas accretion. Spiral arm structures typically serve as important drivers of gas dynamics in galaxies, accumulating gas to produce numerous star-forming regions and young stars. However, the formation of spiral arms remains controversial, with many astronomers arguing that they arise from local perturbations in the disk.

For galaxies composed of different substructures, their global properties represent the integrated characteristics of these components. In other words, substructures within a galaxy influence the properties of the galaxy as a mixture of various components. For example, some green valley galaxies are actually the result of averaging between high star-formation-rate disks and low star-formation-rate bulges, while the common bimodality in galaxy colors reflects the distinct characteristics of bulges and disks. Biases in estimating galaxy physical parameters caused by mixing different substructures may lead to misunderstandings of galaxy formation and evolution. Decomposing galaxies and studying the properties of individual substructures separately can effectively reduce uncertainties introduced by such mixing.

Quantifying the morphology of galactic substructures is fundamental to galaxy decomposition, with radial surface brightness profile fitting being the most commonly used tool for quantifying substructure morphology, as different stellar systems follow different functional forms for their surface brightness radial profiles. For spheroidal systems dominated by random stellar motions (such as elliptical galaxies or classical bulges of disk galaxies, which obey the fundamental plane theory), the surface brightness radial profile approximately follows the de Vaucouleurs law (the r^{1/4} law), expressed as:

$$\Sigma(r) = \Sigma_e \exp\{-7.67[(r/r_e)^{1/4} - 1]\}$$

where r is the radial distance in the galaxy, r_e is the effective radius, $\Sigma(r)$ represents the surface brightness at radial distance r, and Σ_e denotes the surface brightness at the effective radius r_e.

The surface brightness radial profiles of disk systems tend to follow exponential functions, hence such disk structures are called "exponential disks," with the functional form:

$$\Sigma(r) = \Sigma_0 \exp(-r/r_s)$$

where Σ_0 represents the central surface brightness and r_s denotes the disk scale length.

However, fitting spheroidal systems with the r^{1/4} law or disk systems with the exponential law often yields unsatisfactory results. In such cases, a more flexible function—the Sérsic function—has been developed to fit galaxy surface brightness profiles:

$$\Sigma(r) = \Sigma_e \exp\{-\kappa[(r/r_e)^{1/n} - 1]\}$$

where the exponent n is called the "Sérsic index," representing the concentration of light, and κ is a coefficient related to n (thus not an independent free parameter). The Sérsic function unifies the r^{1/4} law and the exponential law: when the Sérsic index n equals 4 (with $\kappa = 7.67$), the Sérsic function becomes the r^{1/4} law; when n equals 1, it becomes the exponential law ($r_e = 1.678 r_s$). By treating n as a free parameter, the Sérsic function can more flexibly fit galaxy surface brightness radial profiles and consequently achieve more satisfactory fitting results. Due to this flexibility, the Sérsic function has become the most widely used function for fitting galaxy surface brightness radial profiles, including for different substructures. The advent of galaxy morphological decomposition software has enabled convenient separation and morphological quantification of various structural components in galaxies.

Nevertheless, uncertainties in galaxy morphological decomposition results represent one of the main challenges in this field, as the decomposition process is highly subjective and variable. Decomposition modes and results can differ completely for different target galaxies. For disk/spiral galaxies, the bulge+disk decomposition mode is commonly adopted, but this two-component approach may be overly simplistic, leaving residual components such as spiral arms in the residual images. Whether excluding these remaining substructures as independent morphological components could seriously affect the fitting remains questionable. Additionally, some galaxies host active galactic nuclei (AGN) at their centers—how does the presence of AGN affect galaxy morphological decomposition results, and how do different decomposition modes influence AGN as an independent component?

To address these questions, we have undertaken this morphological decomposition study of the early-type spiral galaxy M81 (NGC 3031) to quantify its structural composition and investigate how different morphological decomposition modes affect the fitting results of galactic substructures. M81 has a morphological classification of SAab, is located approximately 3.6 Mpc from Earth, and has an angular size of about 26 × 14 . Its proximity and large angular scale enable studies with intrinsically high spatial resolution. Numerous studies have investigated various properties of M81, including stellar population composition, dust distribution, and morphology. This paper presents an in-depth study of M81' s single-band morphology. Building upon this work, our subsequent research will conduct multi-wavelength decomposition of M81, systematically investigating the spectral energy distributions (SED) and stellar population properties of each substructure, as well as the formation and evolution processes of the galaxy as a whole and its individual components.

We describe the data sources and image processing methods in Section 2, present the galaxy morphological decomposition process in Section 3, show the decomposition results in Section 4, discuss them in Section 5, and summarize our conclusions in Section 6. Throughout this paper, 1 corresponds to approximately 1 kpc in physical scale.

2.1 Data Acquisition

As a famous nearby galaxy, M81 has abundant multi-wavelength observational data. For this work, we selected high-resolution Spitzer-The Infrared Array Camera (IRAC) 4.5 µm image data that are relatively unaffected by star-forming regions, irregular clumpy structures, and dust emission. The data originate from The Spitzer Survey of Stellar Structure in Galaxies (S4G) project and can be downloaded from the NASA/IPAC Infrared Science Archive (IRSA) website.

In addition to the Spitzer-IRAC 4.5 µm image data, this work also utilizes Galaxy Evolution Explorer (GALEX) Far Ultraviolet (FUV) image data as a reference for constructing spiral arm models. Since spiral arms are primarily composed of young stellar populations, selecting the GALEX FUV band maximizes the elimination of contributions from old stellar populations when modeling spiral arm structures. This observational band data comes from GALEX data release 6 (DR6) and can be downloaded from the GALEX Guest Investigator website.

In this work, the GALEX FUV images are used only as a reference for spiral arm parameter modeling; the entire galaxy morphological decomposition process and all results are based on the Spitzer-IRAC 4.5 µm images. Figure [Figure 1: see original paper] shows M81 images in both the GALEX FUV and Spitzer-IRAC

4.5 µm bands. The remainder of this section describes the preliminary image processing performed prior to morphological decomposition.

2.2 Galactic Extinction Correction

First, we applied Galactic extinction correction to the images. We adopted the dust extinction model from Fitzpatrick (1999), selecting a ratio of total to selective extinction $R_V = 3.1$. The Galactic extinction value for M81 in the V band is 0.220 mag. The specific correction process was completed using the Python package named "extinction."

2.3 Background Noise Subtraction

Although the Spitzer S4G project had "officially" performed background noise subtraction, they subtracted a constant background value that is unsuitable for images with non-uniform backgrounds. In particular, radial surface brightness profile fitting is highly sensitive to background levels, necessitating the construction of a two-dimensional background noise model for subtraction.

Background noise subtraction first requires identifying background pixels. We employed image segmentation methods with thresholds of 3σ and 5 connected pixels to identify and mark all signal sources, thereby distinguishing between source pixels and background pixels in the image.

After identifying background pixels, all background pixels were used to construct a two-dimensional background model, while all source pixels were excluded from the background. The two-dimensional background model was built using a binning method on background pixels to calculate the scale size of local background variations. This method involves binning background pixels and determining the local background scale by calculating histograms of background pixels under different binning window sizes. The solid black line in Figure [Figure 2: see original paper] shows the probability distribution histogram of the original background image. We tested binning windows ranging from 5 to 30 pixels. As the binning window size increased, the histogram of background pixels became progressively narrower, while the mean of the histogram stabilized until it no longer narrowed further, at which point local background pixels were all binned into the same pixel. We found that a binning window larger than 20 pixels achieved stable histogram behavior. The dashed black line in Figure [Figure 2: see original paper] represents the probability distribution histogram for a binning window of 20 pixels.

After determining the local background scale, we divided the observed image into multiple rectangular subregions large enough to encompass foreground stars but smaller than the local background scale. Through experimentation, we adopted a relatively conservative region size of 124 pixel × 104 pixel. Each such region was then combined into a single pixel assigned the median value of 3σ of all pixels in that region, discarding regions where background pixels accounted for less than 90% of the total. This produced a low-resolution two-dimensional background image, which was then restored to the original image dimensions using bicubic interpolation to create a background model image. Subtracting this background model from the original image yielded the background-subtracted data. We define background uncertainty as the uncertainty introduced by background subtraction, specifically the standard deviation of all background pixel values after subtraction. The background subtraction results are shown in Figure [Figure 3: see original paper]. The morphological decomposition study of galaxy M81 in this work is based on the background-subtracted image.

3 Galaxy Image Morphological Decomposition Process

In this work, we utilize the GALFIT software for galaxy morphological decomposition. In addition to the image to be decomposed, GALFIT requires input of a mask image, a sigma image, and a point spread function (PSF) image. This section describes the creation of these images and the galaxy decomposition modes we employ.

3.1 Creation of Mask, Noise, and PSF Images

The mask image is used to exclude certain pixels from fitting, eliminating the influence of other bright sources and bad pixels on galaxy decomposition. Masked targets include foreground stars, non-numerical signals, and saturated pixels.

Foreground stars are the primary masking targets. In our work, foreground stars are divided into two categories: those outside the M81 coverage area (non-overlapping with the galaxy) and those overlapping with M81. Therefore, determining the sky coverage of M81 is necessary before detecting foreground stars. We use isophotes to define the extent of M81. After fitting elliptical isophotes for M81, we adopt the standard elliptical isophote with brightness equal to the background uncertainty as the galaxy edge. This ellipse has a center position of Right Ascension (RA) = 148.888221°, Declination (Dec) = 69.065295°, a semi-major axis of 750 , a semi-minor axis of 450 , and a position angle of $-20°$ (this ellipse is also used as the elliptical aperture for subsequent aperture photometry). All foreground stars outside this ellipse are marked using the image segmentation method described in Section 2.3.

For foreground stars within the elliptical aperture, we employ a local detection method. Similar to the approach in Section 2.3, we divide the interior of the ellipse into multiple subregions and set a threshold in each subregion to define pixels above the threshold as foreground stars, with thresholds varying by subregion. Visual inspection is performed, with manual additions or removals as necessary. Other masking targets are marked manually.

Figure [Figure 4: see original paper] shows the M81 image with all foreground stars removed to verify the masking effect. This image was created by replacing pixel values of masked foreground stars in the observed image with the median of surrounding pixels.

GALFIT employs a least-squares fitting principle and requires a noise image for the calculation. The noise image includes Poisson noise and readout noise, following the formula:

$$\sigma_e^2 = \sigma_P^2 + \sigma_R^2$$

$$\sigma_P = \sqrt{I_e}$$

where σ_e represents the input noise image, σ_P denotes Poisson noise, σ_R represents readout noise, and I_e is the background-unsubtracted observed image in units of electrons. Calculating Poisson noise requires converting to electron units using the GAIN parameter from the image header. Readout noise is recorded in the header as the RONOISE parameter. The resulting noise image must be converted to the same units as the observed image.

The PSF image serves two purposes in GALFIT galaxy morphological decomposition: fitting point sources in the image and convolving model images to match spatial resolution.

In this work, we create the PSF image by identifying as many isolated, relatively bright foreground stars as possible in the background-subtracted image that are free from bad data and contamination from nearby sources. Through multiple iterations, we construct an effective point spread function (ePSF) model image, requiring that foreground star samples be sliced with the star centered in the slice. The quality of the ePSF model can be verified through GALFIT fitting by checking whether GALFIT can satisfactorily fit foreground stars using only the ePSF model, with no significant residuals remaining in the residual image indicating a reliable ePSF model.

Figure [Figure 5: see original paper] shows the mask, noise, and ePSF images produced through the above methods and procedures. The operations were implemented using the Python package photutils.

3.2 M81 Morphological Decomposition Modes

This section describes the substructures to be fitted during galaxy decomposition, function selection, modeling approaches, and criteria for model quality assessment. The bulge and disk are the most common fundamental substructures in galaxies, contributing significantly to galactic mass and luminosity and largely determining galaxy formation and evolution. The scientific goal of this work is to investigate M81' s substructures and quantify their morphological parameters. We treat the bulge and disk as the basic substructures of M81, adding different functions in various decomposition modes to fit other substructures. Multiple decomposition modes help investigate how fitting different substructures affects the morphological parameter results for the bulge and disk.

GALFIT includes numerous built-in functions, such as the Sérsic function, exponential function (simplified as "Expdisk" in GALFIT, which we use hereafter to denote the exponential function for disk fitting), Gaussian function, and PSF function. These are called "basic model functions," with the Sérsic function being the most commonly used for describing radial surface brightness profiles of systems. Due to its high degree of freedom, it can be widely applied to model various substructures including bulges, disks, and bars. The Expdisk function is a special case of the Sérsic function with index $n = 1$, while the Gaussian function corresponds to $n = 0.5$. Basic model functions are used to fit substructures with uniform and regular surface brightness. To fit irregular substructures with non-uniform surface brightness such as spiral arms and rings, GALFIT includes two "advanced functions": azimuthal functions and truncation functions. These advanced functions cannot be used alone and must be superimposed on a basic model function to modify it into special irregular shapes. The azimuthal function includes a coordinate rotation function that, when superimposed on a basic function, can produce spiral arm structures. Truncation functions truncate basic functions to create ring structures or breaks.

In addition to the bulge and disk, M81 features two magnificent spiral arms, hosts an AGN at its center, and contains a faint spiral-like substructure within the bulge. We model these substructures sequentially. We select the highly flexible and commonly used Sérsic function as the basis for all substructures, superimpose coordinate rotation or truncation functions on the Sérsic function to construct spiral arm structures, and use the PSF function to fit the central AGN structure. Many studies utilize the Expdisk function to fit galactic disks, but we do not follow this convention because the Sérsic index of the disk is also a parameter we aim to explore, particularly to examine how fitting different substructures affects the disk' s concentration.

All model coordinates in the image follow elliptical distributions. When fitting spiral arms, the coordinate rotation function forcibly redistributes the coordinates of each pixel originally following elliptical distributions according to a new pattern, effectively warping the original elliptical function and enabling fitting of various spiral arm morphologies. M81' s outer spiral arms have relatively low brightness compared to the bulge and disk in the IRAC 4.5 µm band. To ensure construction of a reasonable outer spiral arm model, we use the exceptionally clear spiral arm structure in the GALEX-FUV image as a reference. As seen in Figure [Figure 1: see original paper], the outer spiral arms do not directly connect to the bulge but exhibit a distinct "empty region" inside the arms, necessitating consideration of truncation when constructing the outer spiral arm model. When fitting M81' s outer spiral arms, we superimpose both coordinate rotation and truncation functions on the Sérsic function to build the spiral arm structure. We first fit the outer spiral arm model on the GALEX-FUV image, then apply this model to fit the Spitzer-IRAC 4.5 µm image.

The coordinate rotation function in this work takes the form of a power-law hyperbolic tangent coordinate rotation, expressed as:

$$\theta(r) = \theta_{\text{out}} \tanh[(r/r_{\text{out}})^{\alpha}] + \theta_{\text{incl}} + \theta_{\text{sky PA}}$$

where $\theta(r)$ represents the rotation angle at radius r, r_{in} denotes the radial distance where the spiral arm begins, and r_{out} indicates where it ends. When r is less than r_{out}, the spiral arm form is primarily controlled by the tanh function, while the power-law term governs the spiral arm characteristics beyond r_{out}, with α being the power-law slope. θ_{out} represents the rotation angle at the arm' s end radius r_{out}, so the winding tightness of the spiral arm is jointly controlled by θ_{out} and r_{out}. When r is smaller than the arm' s starting radius r_{in}, $\theta(r)$ remains nearly constant, commonly used for fitting galactic bars. For non-barred galaxies, r_{in} is often set to 0. The inclination angle of the spiral arm plane is θ_{incl}, while $\theta_{\text{sky PA}}$ is the position angle, with these two parameters together defining the model' s projection on the celestial sphere.

The truncation function in this work is mathematically expressed as:

$$P(x, y) = \tanh[(r - r_{\text{break}})/\Delta r_{\text{soft}}]$$

where $P(x, y)$ represents the truncation factor at coordinates (x, y). The truncation function truncates models by multiplying the original flux distribution inside or outside the truncation region by the factor P or $1 - P$, respectively. (x_0, y_0) are the central coordinates, q is the axis ratio, and θ_{PA} is the position angle of the truncation function. r_{break} is the break radius, indicating where the truncated model flux decreases to 99% of its original value. Δr_{soft} is the softening length, defined as $r_{\text{soft}} - r_{\text{break}}$ or $r_{\text{break}} - r_{\text{soft}}$ for external or internal truncation, respectively, where r_{soft} is the radius at which the truncated model flux drops to 1% of its original value.

In addition to functions for fitting extended structures, the PSF function is most commonly used for fitting point-like structures. However, different datasets may exhibit completely different PSF shapes, requiring users to provide PSF images for fitting point sources or for image convolution. The PSF model image in this work comes from the ePSF image created in Section 3.1.

Before beginning galaxy decomposition, a template file must be provided manually for GALFIT to read. The template file includes two parts: parameters that constrain the fitting process and initial guesses for model functions. GALFIT requires manual input of several parameters that constrain the fitting process, such as fitting window size and PSF convolution box size. All these parameters are set according to recommendations from the Frequently Asked Questions (FAQ) on the GALFIT website. The fitting window and PSF convolution kernel size can significantly affect fitting time and accuracy. In principle, both should be as large as possible to fully encompass all pixels of the target galaxy and

PSF, but excessively large windows reduce fitting speed. Therefore, selecting appropriate window sizes improves fitting efficiency. Our images have a sufficiently large field of view, so we select a fitting window of 2000 pixel × 2000 pixel, which is sufficient to include all of M81 and a substantial background region. The convolution kernel is set to 80 times the full width at half maximum (FWHM) of the image PSF. Pixel scale and photometric zero point are set to 0.75 /pixel and 18.32 mag, respectively, following the Spitzer telescope handbook.

Before commencing morphological decomposition fitting, initial model parameters must be set. For relatively simple models without coordinate rotation or truncation functions, initial parameters have minimal impact, particularly for single Sérsic function fitting, where even extremely unreasonable initial settings converge to the same stable result. However, for coordinate rotation and truncation functions, initial parameter settings affect GALFIT fitting. Based on our experience in this work, initial parameters influence the fitting time for coordinate rotation and truncation functions, with reasonable parameter guesses typically yielding shorter fitting times. For parameter setting, we adopt a relatively empirical approach to estimate initial values for all functions: before inputting initial parameters, we manually create an artificial model that visually resembles the target. This artificial model is constructed by manually adjusting parameters and verifying similarity to the target through image output and visual inspection—for example, reducing brightness if the artificial model appears brighter than the target, or increasing the effective radius if it appears smaller. We then use the parameter values from this artificial model as initial settings. Since prior conditions for these complex irregular models have greater influence on fitting, the goal of creating a good artificial model is to provide a sound prior. Note that except for the outer spiral arms, which are modeled manually based on the GALEX-FUV image, artificial modeling of other substructures is performed on the Spitzer-IRAC 4.5 μm image. Because spiral arm models require superimposing coordinate rotation or truncation functions on the Sérsic function, they have more free parameters than models describable by a uniform single Sérsic function. Consequently, parameter setting for spiral arm models requires more time and effort than for regular models like bulges and disks, necessitating repeated experiments to ensure sufficiently realistic fitting results. To ensure relative independence among all decomposition strategies, initial parameter settings for different strategies are estimated using the same method described above, meaning we assume each new galaxy decomposition strategy experiment begins as if it were the first.

In this work, we employ an empirical method to estimate GALFIT decomposition fitting errors. We artificially add or subtract a constant value equal to 1σ of the background uncertainty to the image to be decomposed and refit, using the new fitting results as upper and lower error bounds. This method is applied to error estimation for all parameters except magnitude. Uncertainty in magnitude (or brightness) estimation arises not only from background uncertainty but also from elliptical aperture errors and telescope instrument calibration errors.

Therefore, we adopt the orthogonal combination (i.e., the square root of the sum of squares) of elliptical aperture error, calibration error, and background uncertainty as the error for magnitude (or brightness).

4 Results Presentation

In this work, we employ six modes (i.e., six substructure combinations) of increasing complexity to decompose the galaxy in the Spitzer-IRAC 4.5 µm image: - Single component: Sérsic (M81 as a whole) - Two components: Sérsic (M81 as a whole) + PSF (AGN) - Two components: Sérsic (bulge) + Sérsic (disk) - Three components: Sérsic (bulge) + Sérsic (disk) + PSF (AGN) - Four components: Sérsic (bulge) + Sérsic (disk) + PSF (AGN) + Coordinate rotation-Truncated-Sérsic (outer spiral arms) - Five components: Sérsic (bulge) + Sérsic (disk) + PSF (AGN) + Coordinate rotation-Truncated-Sérsic (outer spiral arms) + Coordinate rotation-Sérsic (inner spiral arms)

For each mode, we measure the radial surface brightness profiles of the galaxy as a whole and each substructure component for comparison with the models. Surface brightness radial profiles are measured by drawing isophotes on the foreground-star-removed M81 image (see Figure [Figure 4: see original paper]) to sample surface brightness. All isophotes share the same center, axis ratio, and position angle as the M81 photometric aperture. This same set of isophotes is used uniformly for all substructure images. Figures [Figure 6: see original paper]–[Figure 11: see original paper] display the result images and surface brightness radial profiles for each decomposition mode, Figure [Figure 12: see original paper] shows the fitted results for each model substructure, and Table records the morphological parameter values for substructures in each mode. The following subsections present the analysis results for each mode.

4.1 Single-Component Fitting (M81 as a Whole)

Single-component fitting using only a Sérsic function yields an overall Sérsic index of 4.29 for M81. Photometric results from the original and model images show that the model magnitude from single-component fitting is consistent with aperture photometry results on the foreground-star-removed image (6.78 ± 0.02 mag). In Table , the luminosity fraction is defined as the ratio of the flux in the substructure model image (or the sum of all substructure model images) to the total flux of the original galaxy within the same aperture. Since models may overestimate or underestimate galaxy brightness to varying degrees, the sum of all substructure fractions does not strictly equal 100%. In the single-component fitting results, the M81 whole-galaxy model slightly overestimates M81' s brightness, yielding a luminosity fraction of 100.51%. The residual image contains 12.73% of the total luminosity, primarily contributed by residual spiral arm structures, a small amount of bulge and disk, and other stars.

However, as shown in Figure [Figure 6: see original paper], fitting with only a single Sérsic function is a crude method for measuring overall galaxy properties. The figure reveals that the model image underestimates the galaxy' s position angle; the residual image shows that the model overestimates brightness in small-radius regions and inter-arm areas while underestimating brightness in spiral arms and the disk, leading to overfitting in inter-arm regions and some spiral arms while leaving numerous substructures remaining in the residual image. The surface brightness radial profile clearly demonstrates that the ellipticity and position angle of the single-component fitting model only approximate the average observed values, failing to accurately reflect their radial variation trends. Moreover, the model significantly overestimates M81' s brightness beyond 400 , with the match between model and observed images gradually deteriorating with increasing radius. This indicates that the single-component Sérsic function has limitations in estimating galaxy surface brightness profiles because the morphological complexity of galaxies prevents their overall surface brightness radial profiles from strictly following any particular functional form.

Single-component fitting of M81' s morphological composition represents an overly simplistic approach.

4.2 Two-Component Fitting (M81 as a Whole + AGN)

M81 hosts a low-luminosity AGN at its center. Unlike radiation from the host galaxy, AGN radiation does not belong to any stellar population. However, AGN presence may influence galaxy dynamics, morphology, physical properties, and even formation and evolution. Observationally, failing to account for AGN contributions can bias measurements of host galaxy properties. Therefore, how to subtract AGN contributions when measuring galaxies has always been an important question in galaxy studies. In this work, we attempt to separate the AGN from the host galaxy through morphological decomposition.

We fit M81 as a whole and the AGN using Sérsic and PSF functions, respectively. The results are shown in Figure [Figure 7: see original paper], with substructure images in Figure [Figure 12: see original paper] and parameter values recorded in Table . Figure [Figure 7: see original paper] shows that the model and residual images differ little from the single-component fitting results; the radial surface brightness profiles are also similar, with the model failing to accurately describe the radial variation trends of ellipticity and position angle. Similarly, the model overestimates brightness in the outer regions beyond 400 from the galaxy center. Because M81' s AGN is faint, its impact on the host galaxy is weak.

In Table , the AGN is much fainter than M81 as a whole (a 6 mag difference). After adding the AGN component, the effective radius of M81 as a whole increases by 24.3%; the Sérsic index decreases by 9.32%; axis ratio and position angle remain almost unchanged. Adding the AGN model reduces the luminosity fraction of M81 as a whole by 0.79%, while the AGN itself contributes only 0.64% of the total luminosity. The most significant change is in the effective radius, resulting from the redistribution of brightness in the M81 whole-galaxy model after accounting for the AGN, though this change is smaller than the error introduced by background uncertainty. The residual image contains 12.38% of the luminosity, similar to the single-component fitting result.

4.3 Two-Component Fitting (Bulge + Disk)

For galaxies with both bulge and disk structures, the bulge+disk two-component decomposition is commonly used for morphological decomposition. M81 is such a galaxy, so the bulge+disk two-component morphological decomposition (two Sérsic functions) is included among our six modes.

Figure [Figure 8: see original paper] presents the image results for the two-component (bulge+disk) decomposition, with component model images shown in Figure [Figure 12: see original paper]. Compared to single Sérsic function fitting, the two-component (bulge+disk) fitting better describes both the overall and local morphology of M81. The model image' s size, axis ratio, and position angle are all very close to those of the observed image. The residual image shows that the model successfully separates the bulge and disk from the observed image, leaving only two bright outer spiral arms; the inner spiral arms and a small bar-like structure at the galaxy center remain in the residual image. The model' s radial variations in ellipticity and position angle are also consistent with observations. The previous overestimation of the radial surface brightness profile beyond 400 is significantly improved. The bulge and disk show distinctly different sizes, ellipticities, and position angles, explaining why a single Sérsic function cannot adequately describe M81' s morphology.

In Table , the brightness difference between the bulge and disk is small, only about 0.3 mag. In terms of luminosity fractions, the bulge and disk account for 42.00% and 56.81% of the total flux, respectively, indicating comparable brightness. This demonstrates that even in the 4.5 µm band, which primarily traces old stellar radiation, the disk' s brightness is non-negligible. The bulge' s effective radius (r_e) is only about one-third that of the disk, while the bulge' s Sérsic index ($n = 5.18$) is much larger than the disk' s ($n = 1.17$). This shows that although the bulge and disk have similar brightness, the bulge is concentrated in the galaxy' s inner regions, while the disk is more extended and flatter. The bulge and disk have significantly different axis ratios and position angles, contributing to the radial variations in ellipticity and position angle seen in the surface brightness profiles. The model image from the two Sérsic functions also accurately predicts M81' s brightness within the error range. The residual image contains 10.12% of the luminosity, primarily contributed by residual outer spiral arms, inner spiral arms, and other stars.

4.4 Three-Component Fitting (Bulge + Disk + AGN)

We then add an AGN component to the bulge+disk two-component basis, with results shown in Figure [Figure 9: see original paper] and Figure [Figure 12: see original paper] and Table . In this mode, the bulge and disk results are essentially consistent with those from the pure two Sérsic function decomposition. The AGN is only about 14 mag, much fainter than the bulge and disk, with a luminosity fraction of approximately 0.13%. The residual image shows no significant change compared to the two Sérsic function result, with a luminosity fraction of about 10.10%.

4.5 Four-Component Fitting (Bulge + Disk + AGN + Outer Spiral Arms)

Previous results all show obvious spiral arm structures in residual images. Therefore, we add an outer spiral arm component to the previous decomposition mode, yielding a four-component decomposition of bulge+disk+AGN+outer spiral arms (based on previous results, M81' s spiral arms appear to consist of discontinuous inner and outer sections; this section considers only the outer spiral arms, while the next section will include the inner spiral arms).

Unlike other substructures, spiral arms require superimposing coordinate rotation and truncation functions on a uniform Sérsic index, resulting in more free parameters than uniformly smooth structures and making initial parameter settings more influential. Additionally, in the near-infrared band, spiral arms may be submerged by other substructures, making initial parameter estimation more difficult. Therefore, we utilize the GALEX-FUV image to determine initial parameters for the spiral arms.

The specific approach involves manually adjusting parameters to create a model consistent with the FUV image, then using these parameter values (with simple unit conversion) as initial parameters for fitting the Spitzer-IRAC 4.5 µm image (with spiral arm brightness set 2 mag brighter than the bulge). Since the outer spiral arms are truncated at approximately 100 from the galaxy center, truncation must be included in the outer spiral arm modeling.

The four-component decomposition results for bulge+disk+AGN+outer spiral arms are shown in Figure [Figure 10: see original paper] and Figure [Figure 12: see original paper] and Table . Figure [Figure 10: see original paper] and Figure [Figure 12: see original paper] demonstrate that after adding the outer spiral arms, the similarity between model and observed images improves noticeably; residual images show almost no remaining outer spiral arms, leaving only small-scale bright star-forming regions and inner spiral arms. The model' s surface brightness radial profile also provides a better fit to observations; the model' s curves of ellipticity and position angle versus radius are more consistent with observations. The previous overestimation of surface brightness in the galaxy' s outer regions is also significantly improved, with the difference between model and observed surface brightness being only about 0.6 mag even at radii approaching 700 . Comparing individual substructures, adding the outer spiral arm model has no obvious effect on the bulge model image, but causes slight changes in the disk' s size.

Table shows that adding spiral arms does not produce major effects on the bulge and disk, with most parameter changes smaller than background-induced errors. The parameter showing the largest change is the disk' s effective radius (r_e), which decreases by about 11% after adding the outer spiral arms. Additionally, including the outer spiral arm model causes subtle changes in the position angles of the bulge and disk. In terms of luminosity, the outer spiral arms contribute only 5.42% of the galaxy' s total luminosity, while the luminosity fractions of the bulge and disk both decrease slightly after adding the outer spiral arms, with the AGN showing little change. The residual image contains approximately 9.15% of the luminosity, primarily from inner spiral arms and other stars.

4.6 Five-Component Fitting (Bulge + Disk + AGN + Outer Spiral Arms + Inner Spiral Arms)

All previous results reveal the presence of an inner spiral arm in M81. Many studies of M81 have identified this substructure that is discontinuous with the outer spiral arms. These studies indicate that M81' s inner and outer spiral arms follow the same rotation pattern but may consist of different materials. Because the inner spiral arm lies in the small-radius region directly adjacent to the bulge, failing to consider this substructure may cause light from the inner spiral arm to be assigned to the bulge or disk in the decomposition, introducing errors. Therefore, in this section we include this structure as an independent morphological component in the fitting model.

Figure [Figure 11: see original paper] shows the fitting results using these five morphological components, with model images for each substructure component shown in Figure [Figure 12: see original paper]. Compared to other decomposition modes, adding the inner spiral arm yields the closest match between model and observed images; no obvious residual substructures remain in the residual image. This indicates that all prominent substructures in M81 have been accounted for in the model. The surface brightness radial profile shows that the model can essentially predict M81' s surface brightness, ellipticity, and position angle well across all radii.

Table clearly shows the quantitative changes in bulge and disk properties after adding the inner spiral arm. The bulge' s primary changes occur in ellipticity and position angle, varying by 6% and 8% respectively, with other parameters showing minimal changes. Adding the inner spiral arm has a very significant effect on the disk: after including the inner spiral arm, the disk' s brightness decreases by about 0.5 mag, its effective radius (r_e) decreases by approximately 38%, its Sérsic index n decreases by about 50%, and its luminosity fraction drops by 18.68%. The inner spiral arm itself contributes 17.06% of the total luminosity. This demonstrates that when the inner spiral arm is not independently fitted in the model, its light is assigned to the disk. Other substructure parameters show minimal changes. The residual image contains about 8.58% of the luminosity, primarily from remaining foreground stars and other stars in M81. Adding the inner spiral arm does not affect the outer spiral arm fitting results.

5.1 Comparison of Main Results from Six Galaxy Decomposition Modes

Table records all parameter values, enabling quantitative comparison of the effects of different galaxy decomposition strategies. For the total model magnitude, except for the single-component model whose magnitude matches the observed image, all other decomposition strategies slightly underestimate by 0.02 mag, a bias lower than the error introduced by background uncertainty. This indicates that all galaxy decomposition strategies can accurately predict brightness.

Our results demonstrate that implementing different decomposition modes indeed leads to biases in estimating overall galaxy morphology. The overly simplistic single-component (single Sérsic function) decomposition mode yields a Sérsic index n characteristic of the bulge and an effective radius r_e characteristic of the disk, with axis ratio and position angle approximately averaging those of the bulge and disk. This confirms that galaxies like M81 are complex morphological systems containing multiple substructures, and that global galaxy properties represent the integrated characteristics of individual substructures.

Except for the single-component decomposition mode, the other five morphological decomposition modes show no significant variations in bulge morphological parameter values. Using each parameter's minimum value as a baseline, the maximum variation amplitudes for bulge luminosity fraction, magnitude, effective radius, Sérsic index, axis ratio, and position angle are 6.90%, 0.77%, 9.40%, 6.36%, 7.14%, and 13.10%, respectively. Except for position angle, bulge parameter variations are smaller than errors from background uncertainty. For position angle, the bulge+disk two-component and bulge+disk+AGN three-component decompositions yield consistent results, while the bulge+disk+AGN+outer spiral arms four-component and bulge+disk+AGN+outer spiral arms+inner spiral arms five-component decompositions increase and decrease the position angle by 8.41% and 4.41%, respectively. This result indicates that bulge position angle estimates are susceptible to spiral arm influence; even outer spiral arms that do not overlap with the bulge can cause bulge position angle estimation biases larger than background uncertainty.

Compared to the bulge, the disk structure exhibits relatively large property variations across different decomposition modes. Using each parameter' s minimum value as a baseline, the maximum variation amplitudes for disk luminosity fraction, magnitude, effective radius, Sérsic index, axis ratio, and position angle are 64.52%, 7.30%, 38.30%, 93.54%, 4.26%, and 26.06%, respectively. The bulge+disk two-component and bulge+disk+AGN three-component decompositions yield essentially consistent results. Compared to these, adding outer spiral arms in the four-component decomposition changes the above parameters by 6.64%, 0.95%, 12.34%, 5.26%, 2.08%, and 10.59%, respectively. In the five-component decomposition with inner spiral arms added, the disk parameters change by 23.15%, 7.30%, 24.89%, 85.71%, 4.25%, and 26.06%, respectively.

Therefore, except for the inner spiral arm, whether other substructures are fitted independently does not significantly affect disk parameter values. For position angle, the disk shows larger variations than the bulge across different modes because the disk directly overlaps with spiral arms. Whether the inner spiral arm is fitted independently has the greatest impact on disk parameters because when the inner spiral arm is not considered separately in the model, its light is assigned to the disk.

All mode experiments indicate that the AGN has minimal impact on overall galaxy and substructure fitting. Across the six galaxy decomposition modes, AGN magnitude variations (relative to the minimum value) remain within 14.33%, and luminosity fraction variations within 0.52%. This suggests that AGN brightness estimates are also not easily affected by other substructures. However, the AGN in the single Sérsic function + PSF two-component decomposition mode is two magnitudes brighter than in other modes because the absence of a separate bulge component leads to overestimation of AGN brightness (including some bulge light).

5.2 Applicability of Different Galaxy Decomposition Modes

Through experiments with multiple decomposition modes, we find that more complex modes require longer GALFIT running times, particularly those involving coordinate rotation functions for spiral arm modeling and truncation functions, which have large parameter spaces and consequently require more time per fitting than simple models, along with higher computer configuration requirements. Spiral arm or truncation modeling requires manual parameter adjustment, making such modes clearly limited for large-sample galaxy studies. Furthermore, our results show that adding outer and inner spiral arms causes varying degrees of change in bulge and disk parameters. Therefore, this work can provide empirical references for other galaxy morphological decomposition studies.

In the bulge+disk two-component and bulge+disk+AGN three-component decompositions, bulge and disk results differ little. Based on our experience, both modes yield very stable results that are not easily affected by initial parameters; even with unreasonable initial parameter estimates, these decomposition modes converge to consistent, reasonable results, and their running times are the shortest (except for the overly simplistic single Sérsic function single-component and single Sérsic function + PSF two-component decompositions). Comparing these two modes reveals that adding a PSF function has little impact on bulge and disk fitting. However, we recommend including a PSF function to fit the galaxy’ s central structure because although M81’ s AGN is not bright, for galaxies with brighter AGN (or PSFs with prominent halos), adding a PSF function will improve decomposition accuracy while having minimal impact on overall computational time. Therefore, we recommend the bulge+disk+AGN three-component fitting as the most suitable mode for large-sample galaxy morphological decomposition studies.

In our work, the bulge+disk+AGN+outer spiral arms four-component and bulge+disk+AGN+outer spiral arms+inner spiral arms five-component decompositions most accurately reproduce the galaxy' s overall observational characteristics, but these two modes require the longest computation times and are therefore more suitable for in-depth studies of individual galaxies, such as measuring spiral arm parameters separately. Some studies suggest that substructures located outside the bulge (such as spiral arms) have minimal impact on bulge morphological parameter fitting results (compared to substructures near the bulge, such as bars). Our results partially support this conclusion but also reveal differences: our four-component and five-component decomposition results show that whether outer spiral arms are fitted independently indeed has minimal impact on both bulge and disk, while in the five-component decomposition, whether the inner spiral arm near the bulge is fitted independently also has minimal impact on the bulge but significantly affects the disk. We therefore recommend that for substructures near the bulge, whether to fit them independently may not affect bulge fitting (similar to substructures outside the bulge), but can significantly impact disk structure fitting.

5.3 Impact of AGN Presence on Galaxy Decomposition

As a central substructure, AGN brightness may influence measurements of the host galaxy. An important aspect of this work is investigating AGN effects across different galaxy decomposition modes. To this end, we additionally performed a four-component decomposition experiment of bulge+disk+outer spiral arms+inner spiral arms. Figure [Figure 13: see original paper] shows the image results from this experiment, with component model images in Figure [Figure 12: see original paper] and parameter values recorded in Table .

Compared to the five-component decomposition with AGN, we find that whether the AGN component is fitted independently has very minimal impact on all substructure parameters. The largest change is in the bulge' s Sérsic index, which decreases by about 4.70% after adding the AGN; other parameters change by less than 1%. All parameter variations are much smaller than errors from background uncertainty. No obvious differences are apparent in comparisons of model and residual images or radial surface brightness profiles. The residual image contains about 8.61% of the luminosity, similar to the five-component residual image, with this light primarily from remaining foreground stars and other stars in the galaxy.

Our experiments covering multiple modes from simple to complex demonstrate that adding the AGN affects substructure parameters by only about 1% or less, smaller than background uncertainty errors. Nevertheless, we still recommend fitting the AGN (or galaxy core) independently because M81' s AGN is low-luminosity and thus has minimal impact on decomposition. However, for high-luminosity AGNs, the expected impact would be considerable; even when AGN luminosity or existence is unknown, we recommend independent fitting of the galaxy core.

5.4 More Complex Decomposition Modes

In this work, we employ six galaxy decomposition modes of varying complexity, but we do not believe that more morphological components necessarily yield better models. The most complex model in this work is the five-component substructure model. No obvious morphological components are visible in the residual image from the five-component decomposition, but this does not allow us to conclude that M81 is indeed composed of these five substructure components. Studies suggest that M81’ s inner and outer spiral arms are actually part of a single spiral substructure. However, the inner spiral arm is not visible in M81’ s UV images, indicating at least that the inner and outer spiral arms have different stellar population compositions. Therefore, while we distinguish between inner and outer spiral arms in this work, we cannot prove they are independent substructures. Indeed, adding more components may produce better fitting results, but the dynamical 归属 of these substructures is not a question that morphological decomposition alone can answer. Furthermore, because some substructures have limited brightness and minimal impact on major galaxy components (such as the bulge and disk), we recommend that unless the research goal specifically focuses on these faint substructures, they need not be fitted independently during galaxy decomposition.

5.5 Common Issues in Galaxy Decomposition

In this final discussion section, we offer some lessons learned from this work. First, our results recommend understanding GALFIT software settings for images and parameters before fitting begins. For example, weight, error, or noise images provided by telescope data archives may differ from GALFIT requirements, and inconsistent image formats or units will produce erroneous results. Second, we recommend setting the fitting window (or field of view) large because the quality of models constructed by GALFIT is sensitive to background (though note that large windows reduce fitting speed, so a balance must be struck). Third, frequent use of GALFIT’ s model output function is recommended, especially for complex decompositions, as manually constructing a target-like model beforehand can greatly improve decomposition efficiency. Finally, a potential GALFIT convention is that output filenames must begin with letters rather than numbers, otherwise fitting will not run. We hope these lessons will be helpful to readers.

6 Conclusion

This work presents a morphological decomposition study of the nearby early-type spiral galaxy M81 based on Spitzer-IRAC 4.5 µm images, using the galaxy decomposition software GALFIT to quantify morphological parameters of each substructure in M81 and investigate how different decomposition modes affect fitting of major substructures such as the bulge and disk. We employ six morphological decomposition modes of increasing complexity. The results demonstrate that the overall morphology of a galaxy (i.e., without independently fitting any substructures) represents the integrated characteristics of all substructures present in the galaxy, and that only through morphological decomposition can we comprehensively and thoroughly understand galaxy morphology and related properties.

The main conclusions of this work are as follows: - M81' s bulge is a classical bulge with a Sérsic index of approximately 5, effective radius of about 1.3 kpc, axis ratio of about 0.7, position angle of about −34°, and apparent magnitude of about 7.7 mag, with a luminosity fraction of about 40%. These bulge parameters remain stable across all decomposition modes and are not easily affected by other substructures. - For the disk structure, different morphological decomposition modes yield different results. Except for the five-component fitting, other modes find M81' s disk to have a Sérsic index of about 1.2, effective radius of about 3.8 kpc, axis ratio of about 0.47, position angle of about −26°, and apparent magnitude of about 7.4 mag, with a luminosity fraction of about 56%, making it the brightest substructure in the 4.5 μm image. However, when the inner spiral arm is fitted independently, the disk becomes flatter, with a Sérsic index of about 0.6, effective radius of about 5 kpc, and luminosity fraction of about 35%, becoming the second-brightest substructure in M81 at 4.5 μm. - Spiral arm morphological parameters are relatively stable. The outer and inner spiral arms have magnitudes of about 9.8 mag and 8.7 mag, and luminosity fractions of about 6% and 17%, respectively. Both substructures are not easily affected by other components. - AGN results are relatively stable across all morphological decomposition modes. Except for the single Sérsic function + PSF two-component fitting, the AGN magnitude is about 14 mag with a luminosity fraction of about 0.1%. In the single Sérsic function + PSF two-component fitting result, the AGN is brighter (about 12 mag with a luminosity fraction of about 0.64%) due to overestimation of its brightness (including some bulge light) caused by the absence of independent bulge fitting.

Through comparison of results from different morphological decomposition modes, we recommend that the choice of decomposition mode depends on specific research objectives. Large-sample studies are well-suited to the bulge+disk+AGN three-component fitting, while studies of individual galaxies benefit from more complex decompositions with additional components (such as spiral arms). Furthermore, we find that spiral arms (particularly inner spiral arms, when present) have very strong effects on the disk but minimal impact on the bulge. Therefore, we recommend considering spiral arm effects when precise measurement of disk morphological parameters is desired.

This work marks the beginning of our series of studies on M81. Next, we will conduct multi-wavelength morphological studies of M81' s substructures, quantify its morphological K-correction, and employ SED fitting to investigate the spatial distribution (two-dimensional properties) of stellar population components in M81 as a whole and in its substructures. Building upon this foundation, we will attempt to use numerical simulations to 演绎 the formation and evolution of M81 and its substructures.

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