Photometric descompositions

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Abstract

Studying bulges and elliptical galaxies is of great interest for the understanding of the galaxies, as well as, their formation, morphology, and evolution. We have studied the $UGC09067$ galaxy, using photometric decomposition via the `imfit` tool. This way we obtained the best fit 2D image and residuals, and the 1D radial profiles.

1 Introduction

Photometric decomposition is one of the most useful tools to understand and study galaxies observed. This type of method began in the early 80s. Pioneering photometric decomposition methods were based on modeling the one-dimensional (1D) SB profiles of galaxies as the sum of separate components.
Later with the apparition of CCD cameras, the study of galaxies by hybrid methods, i.e. fitting both the SB and the galaxy ellipticity profiles, was possible. Since then, several codes and tools have been developed to perform 2D bulge+disk photometric decompositions, but most recent algorithms allow for a 2D multi-component photometric decomposition ([1]). Image functions provided with `imfit` include, among others, the usual suspects for galaxy decompositions (Sérsic, exponential, Gaussian), Core-Sérsic, and broken exponential profiles.

In this work, we have used the `imfit` tool to study the $UGC09067$ galaxy. We performed 2D photometric decomposition, searching for the best fit model and obtaining other parameters like the total magnitude of the components and B/T. We will present 2D maps of galaxy models and residuals, and we will plot the 1D profiles overplotting the best fit model.

The main mathematical expressions we will use to fit the different photometric profiles we will study are:

· Exponential profile:

$$I(r) = I_0 e^{-r/h} \tag{1}$$

Where I_0 is the central surface brightness, and h is the disk scale length.

· Sérsic profile:

$$I(r) = I_e \cdot exp\Big[(0.37 - 2n) \cdot \big[(r/r_e)^{1/n} - 1\big]\Big] \tag{2}$$

Where I_e is the effective surface brightness, r_e is the effective radius, and n is the Sérsic index, that modifies the shape of the function.

· Moffat profile:

$$I(r) = I_0 \cdot \Big[1 + (r/\alpha)^2\Big]^{-\beta} \tag{3}$$

Where I_0 is the central surface brightness, β represents the overall shape, and α is a parameter related with the $FWHM$ by:

$$\alpha = \frac{FWHM}{2\sqrt{2^{1/\beta} - 1}}$$

2 Data

Currently, one of the best surveys for astronomical objects research is the Sloan Digital Sky Survey, or SDSS [2]. The SDSS is a multispectral imaging and spectroscopic survey that has created detailed three-dimensional maps of the Universe, as well as, the spectra for more than 3 million astronomical objects.

We have obtained the images and the spectral of the $UGC09067$ galaxy, in the FITS format. This galaxy is well known and studied, located at RA : $14h$ $10min$ $45.462s$, DEC : $+15$ $12min$ $33.91s$ (optical) in ICRS(ep=J200) coordinates, with a redshift of $z = 0.0262$. Morphologically it has been classified as an Sbc type, a spiral galaxy.

Figure 1: Optical image of the UGC 09067 galaxy, obtained from the SDSS.

The SDSS astronomical images are CCD ones. Some basic properties should be taken into account while performing a photometric decomposition, all of them related to the CCD and the telescope operation, the gain, the noise, and the point spread function. First, the gain refers to the magnitude of amplification that the CCD produces, reported in terms of electrons/ADU. The noise is a combination of the different inherent CCD factors that affect the image, like the sky level, the readout noise, the photon noise, and the thermal noise. The sky level is the extra light detected the CCD that comes from non-astrometrical sources, the readout noise is the

noise of the amplifier that converts the charge into a change in the analog voltage, the photon noise comes from the Poissonian nature of photons and finally, the thermal noise comes from spontaneous electrons in the detector due to thermal instabilities.
There is another nuisance effect of galaxy images, known as the point spread function (PSF). It studies the distortion introduced by the telescope optics in the detector. By the effect of the instruments inside the telescope, the light coming from a point of the source is redistributed in a width that varies according to the PSF. In galaxy images, it affects mostly the center of the galaxies, so it is really important to introduce it in the photometric decomposition. The PSF has a shape similar to a gaussian or a Lorentzian distribution, but the wings cannot be accurately described by these two functions, that is why we will use the Moffat distribution, proposed to model the PSF.

The majority of these parameters are explicit in the header of the FITS image:

- Gain: 4.88 (e^{-}/ADU)
- Sky level: 283.44 counts
- Readout noise: 6.25 e^{-}

In our case, the PSF will be performed using a moffatian distribution. The process will be explained in more detail in the methodology section.

3 Methodology

Currently, there exist many software and tools for astronomical image processing and analysis of astronomical data. In this work, we have mainly used the `imfit` image-fitting program [5], specialized for galaxies. `imfit` allows us to perform photometric decompositions in 2D, fitting any image, in FITS format, too many different surface brightness models. As, in this case, we studied the UGC 09067 galaxy and its components, we focused on a Sersic profile, generally used to describe elliptical galaxies and bulges, and an exponential profile, more commonly used for modeling galaxy stellar disks.

Once we characterized all the parameters, they must be included in the `imfit` code used for fitting. `imfit` asks as input an image and a configuration file with the initial conditions for the parameters of the chosen model and the center of the galaxy in the FITS image. Then, proceed with the fits, searching for the best set of parameters that minimize residuals χ^2. Other astronomical objects in the image can bias the fit, so they must be cut out of the image, so we include a mask image in the `imfit` task. Studying the outcomes for the models and limiting the range of the initial conditions, we can reach the most suitable and realistic model for the surface brightness of the studied galaxy.
After all the modeled profiles for the galaxy are known, the `imfit` routine `makeimage` can integrate the total flux of each model and its corresponding magnitude.

Finally, for the verification of the results, the chosen model surface brightness will be generated in 1D and compared with the observed surface brightness profile of the galaxy.

3.1 Galactic center coordinates

The first step for the profile fitting will be to set the central pixel coordinates of our image. For this, we will be using `ds9` software. Opening our data `.fits` image in `ds9` we can set a central region and from that extract the coordinates. This process is illustrated in figure 2.

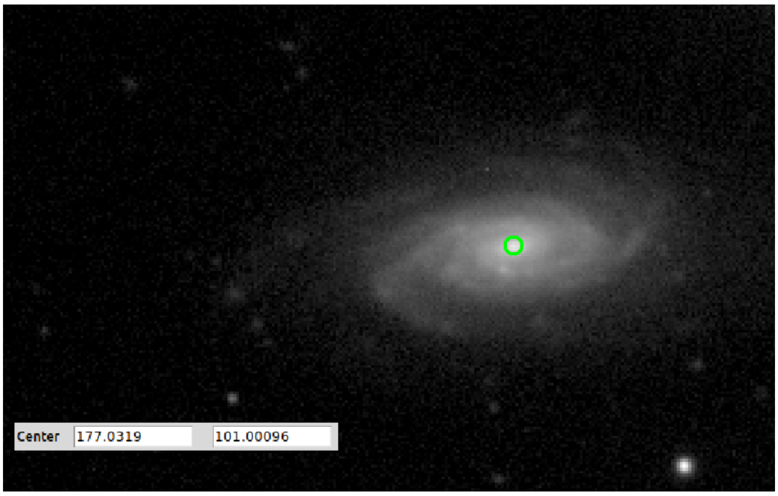


Figure 2: Crop of `ds9` software interface showing the central region of the galaxy and its coordinate values in pixels.

3.2 PSF computing

Another input that `imfit` requires for the model fitting is the PSF of the image. In our case, we will be using a moffatian distribution following the data from the sky of observation. The expression of this profile can be found in equation 3. This contemplates an FWHM of 0.894 arcsec (0.894 pixels) and $\beta = 3.78$, which is the astrometric scattering coefficient. In figure 3 we can see a 2D representation of the Moffat profile computed. This was developed using `makeimage` tool inside the `imfit` package.

3.3 Initial parameter values

Then, we will need to determine the different initial parameters to use in `imfit`. The obtaining of these parameters differ from the two profiles we are using, firstly, for the exponential profile we will need to select the following:

- I_0: Central intensity of the disk, measured in the Y-axis for a line that follows the disk trend.
- h: Disk scale length, this parameter is measured as the value of the axial coordinate at which the intensity has a value of I_0/e.
- PA: The initial value of the Position Angle will be extracted from the trend of the PA figure.
- el: The initial value of the ellipticity will be extracted from the trend of the disk in the figure.

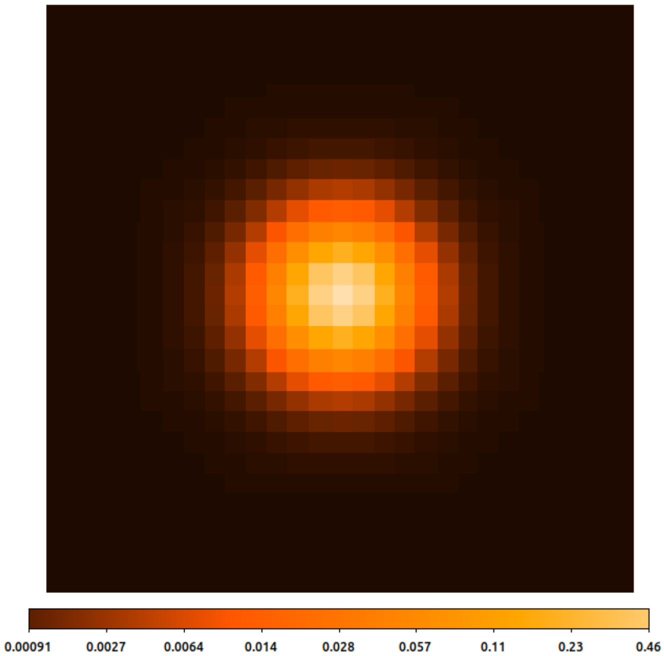


Figure 3: Crop of `ds9` software interface showing the central region of the galaxy and its coordinate values in pixels.

The initial parameters for the sérsic profile are the following:

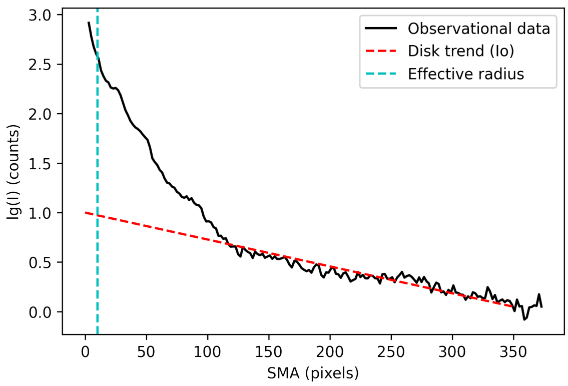
- r_e: SMA value that holds half the total luminosity.
- I_e: Intensity value for SMA equal to the effective radius.
- PA: The initial value of the Position Angle will be extracted from the value at the effective radius.
- el: The initial value of the ellipticity will be extracted from the value at the effective radius.
- n: Sérsic index (n=4 for elliptical profiles and n=1 for disk profiles)

In figure 4 we can see the different parameters set. For the exponential profile, we simply set the different trends in the values, and in the case of the central intensity we continued the disk trend until it crossed the Y-axis (see 4a).

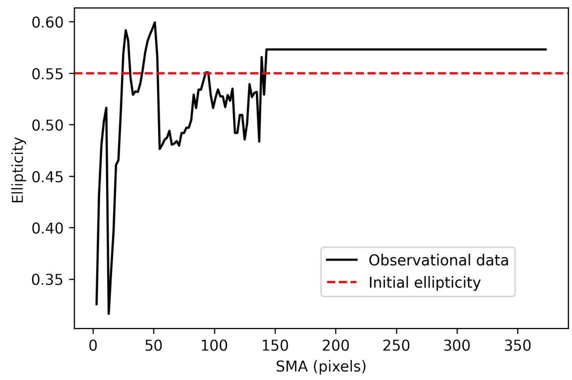
For the sérsic profile, everything we needed was the effective radius value to extract the corresponding values of the Elliptiociy and PA. The effective intensity was also extracted as the intensity value at the effective radius.

In the case of h, it was calculated via the relation mentioned above, and the Sérsic index n was set to a value of 2 because is the value in between the two main models.

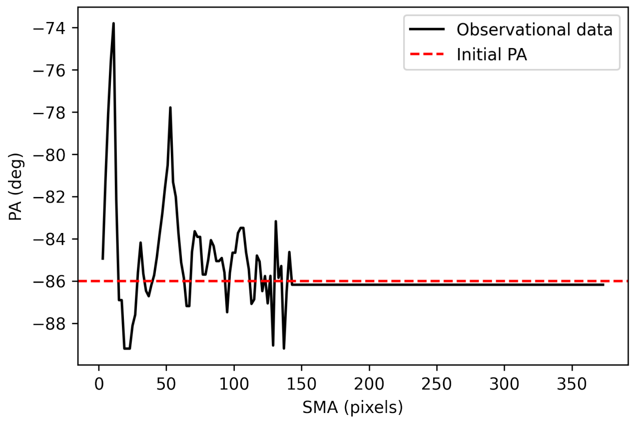
From the Intensity plot, we can see how this galaxy has a very sharp central intensity profile, which will be difficult to model. We can anticipate that the sérsic model for the nucleus will fit correctly for and the disk region is very flat, so an exponential model should work. The sum of



(a)



(b)



(c)

Figure 4: Different plots to set the profile model's initial parameters. In (a), the central intensity of the disk is set and also the effective radius. (b) and (c) show the initial Ellipticity and PA values.

both profiles will maybe differ more from the real data.

All the initial parameters obtained for the sérsic profile and the exponential profile are presented in tables 1 and 2. Notice that the center coordinates of the galaxy were added to these initial parameters.

I_e (counts)	PA (deg)	Ellipticity	r_e (pixels)	X_0 (pixels)	Y_0 (pixels)
100	-88	0.5	30	176	100

Table 1: Initial values of the parameters for the sérsic profile fit.

3.4 Profile fitting

Now that all the parameters are set we can call `imfit` for the model fitting. We will be performing an exponential and sérsic model fit for all the profile distribution to see their behavior, then we will perform a combined exponential and sérsic model.

I_0 (counts)	PA (deg)	Ellipticity	h (pixels)	X_0 (pixels)	Y_0 (pixels)
10	-86	0.55	120	176	100

Table 2: Initial values of the parameters for the exponential profile fit.

4 Results

The output of the `imfit` model fit has been plotted following the expressions we mentioned in the introduction (see equations 1, 2). In figure 5 we can see the three models plotted, the exponential, sérsic, and the combination of both. The χ^2 value of the fit is 8.27, which is a very high value, we will analyze why in the discussion.

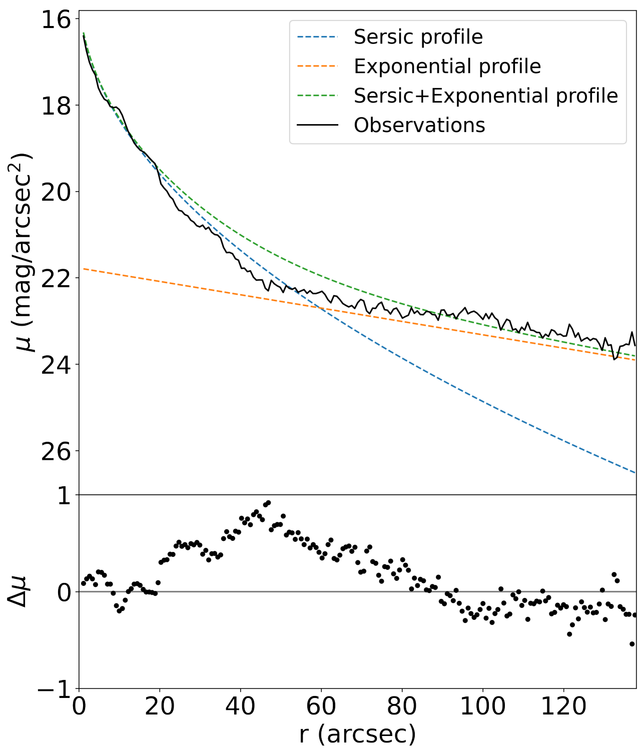


Figure 5: Surface brightness fitting models. In green the exponential model fit, in cyan the sérsic model. The combination of both models is in red. The second figure represent the residuals of the model for each radial value.

	PA (deg)	I_e (counts)	r_e(pix)	ell	n	I_0 (counts)	h (pix)
Disk (exp)	-40.6 ± 0.1	-	-	1	-	9.43 ± 0.26	190.4 ± 0.3
Bulge (sérsic)	-83.6 ± 0.1	56.3 ± 0.6	47.3 ± 0.3	0.53	2.01 ± 0.01	-	-

Table 3: Best fit parameters for the combined exponential and sérsic fitting profile. The error values are extracted from `imfit` output. For the ellipticities the errors were at the order of 10^{-3}.

	Sérsic	Exponential	Sérsic+Exponential
χ^2	8.266807	138.698767	8.274428

Table 4: Residuals for every fitting model used in the computations.

Using the `makeimage` tool we can also obtain the apparent magnitude of the galaxy data. The model created by the program is presented in figure 6 and convolves the profile given by the best parameters in the output of `imfit`.

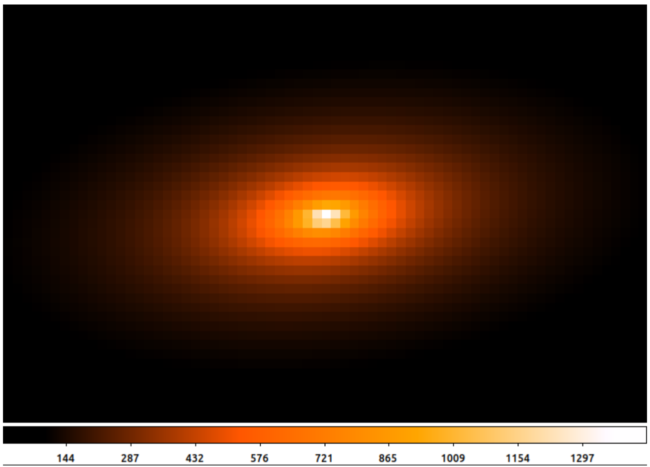


Figure 6: 2D representation of the modelled galaxy performed by `imexam`'s `makeimage` command. The paremeters used to perform the model where the best fit values presented in table 3.

In our case, we were using the infrared filter from SDSS, which lets us with m$_i$. This value has much relevance because we can use it to obtain the absolute magnitude of the galaxy. For this, we will be using the redshift obtained by the CALIFA survey based on the SDSS DR7 spectra (see R. García-Benito et al [3]). This value is z=0.0262, and also matches the one obtained by Christopher M. Springob et al. [4]. We will then obtain the magnitude as follows:

$$M_{\rm i} = m_{\rm i} - 5log(d(\rm pc)) + 5 \tag{4}$$

Where d is obtained with the following expression using a recent value of the Hubble constant $\rm H_0$ = 69.8 ± 0.6 (stat) ± 1.6 (sys) km s^{-1} Mpc^{-1}, obtained by Wendy L. Freedman, 2021 [5].

$$d = \frac{c \cdot z}{H_0} = 112.53 \text{ Mpc} \tag{5}$$

The value of the distance matches very well the one found in the bibliography of d=114.5 Mpc (see Alberto D. Bolatto et al. [6]), in which the distance was calculated via the Tuller-Fisher relation, independent from the redshift.

The value of the apparent magnitude obtained by the `makeimage` combined sérsic and exponential model of the galaxy using the best-fit parameters is:

$$m_{\rm i} = 8.74 \text{ mag}$$

Then we can calculate the absolute magnitude as we mentioned above, the result is:

$$M_{\rm i} = -26.52 \text{ mag}$$

We haven't found a bibliography to compare the data of the relative or absolute magnitudes. Another relevant value obtained in the model fitting is that B/T, the surface brightness of the bulge in comparison with the total, is equal to 1. This is very relevant meaning that all the incoming intensity from the source is coming from the bulge itself. This is why a sérsic-only fitting model has a similar χ^2 value to the combined model of sérsic and exponential. The values of χ^2 will be presented in the discussion section.

5 Discussion & Conclusions

We would like to emphasize the point we made in previous sections. The brightness profile of the disk is very flat in comparison to other galaxies, as well as in comparison to the central bulge. This galaxy is highly influenced by bulge dominance. This makes the fitting process more difficult than other cases.

As we can see in the figure 5, the bulge of the galaxy is highly brighter than the disc. This difference makes it difficult for the software to compute a model that fits both parts. In fact, the sérsic model and combined model fit very good in the central part of the galaxy, meaning the influence of the sérsic model in this region is very high.

Also, as it can be seen in the same figure, the best model to fit the data is the Sérsic+Exponential profile, which even though, it has a slightly higher value of χ^2 than the pure Sérsic profile it is pretty clear than fits better, especially in the outer parts of the galaxy (disc, $r > 50$ pc) since it takes into account the exponential profile used to fit it.

Finally, in this work, we studied the galaxy UGC 09067, via photometric decomposition. We obtained our data from the SDSS and made use of the `imfit` tool to perform the study. We studied the galaxy, via the fitting of the radial intensity profile that it presents. We fitted for three different types of theoretical profiles:

- **Exponential profile**: Used mostly for the modeling of the disc and outer parts of the galaxies.
- **Sérsic profile**: Used for modeling bulges and elliptical galaxies.
- **Sérsic+Exponential**: A combination of the latter, mostly used for the study of spiraled galaxies like the one we studied.

As we already discussed the best model for fitting the profile obtained from the data is the **Sérsic+Exponential** profile, it does not have the lowest χ^2 value (since it is the pure Sérsic profile which has it), but it's pretty clear from Fig. 5 it replicates the profile the best. The other models fitted the sections we expected greatly, exponential for the disc and Sérsic for the bulge, but both failed ant fitting one of the parts. So we conclude that the best fitting profile for this specific galaxy is the **Sérsic+Exponential** and that our results are mostly correct taking into account the assumptions and simplifications made for the study.

References

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